SAND2022-11194C

Progress Toward a Deep Borehole Field Demonstration

Geoff Freeze[1], John Phalen[2], Dirk Mallants[3], David Sassani[4],

[1]*Sandia National Laboratories, Albuquerque, NM, gafreez@sandia.gov*
[2]*Commonwealth Scientific and Industrial Research Organisation, Brisbane, Australia, john.phalen@csiro.au*
[3]*Commonwealth Scientific and Industrial Research Organisation, Adelaide, Australia, dirk.mallants@csiro.au*
[4]*Sandia National Laboratories, Albuquerque, NM, dsassan@sandia.gov*

[leave space for DOI, which will be inserted by ANS]

INTRODUCTION

Various concepts for the geologic isolation of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in boreholes with different diameters and depths have been proposed [1, 2, 3]. Depending on the target geologies and waste forms, these concepts range from low-level waste (LLW) and sealed sources in shallow boreholes (tens to hundreds of meters depth) to intermediate-level waste (ILW) and HLW in intermediate-depth boreholes (≤ ~2,000 m depth) to SNF and HLW in deep boreholes (~2,000 – 5,000 m depth).

Borehole disposal may be particularly attractive for countries with smaller radioactive waste inventories, where the modular cost of a few boreholes may enable safe and economic geologic disposal due to the lower up-front capital investment compared to a mined repository [1].

Robust post-closure waste isolation can be attained in deep vertical boreholes in low-permeability host formations that are hydrologically isolated from overlying circulating groundwater systems. If properly sited and constructed, this deep borehole concept relies almost entirely on the natural system to completely and permanently prevent the waste from being released to the subsurface hydrogeology and biosphere. Engineered seals, emplaced in the borehole above the waste, are relied upon only during the relatively short period of upward flow (< few hundreds of years) due to thermal perturbation from waste form decay heat. This almost exclusive reliance on the deep natural system barriers is unlike that of mined geologic repositories, which are typically located at shallower depths that are within the circulating groundwater systems [4, 5]

These shallower mined repositories rely on a combination of engineered and natural barriers to prevent or reduce releases of radioactivity into the subsurface hydrogeology and biosphere for the very long periods of post-closure performance. Similar to mined repository systems, the intermediate-depth and shallow borehole concepts may require, depending on the inventory and geology, greater reliance on a combination of engineered barriers (e.g., waste form, waste container, borehole fill materials and seals) and natural barriers for substantial periods of the post-closure performance.

For all of these borehole disposal concepts, a field demonstration of disposal activities would significantly contribute to confidence in concept viability. Specifically, full-scale demonstrations of surface handling and downhole emplacement using surrogate waste canisters (i.e., containing no radioactive materials) would inform the safety and feasibility of pre-closure operations; and demonstrations of borehole sealing and of downhole system characterization techniques would inform the safety and feasibility of post-closure waste isolation [1, 5, 6, 7].

This paper summarizes the worldwide status of planning for deep borehole field demonstration activities that would advance the technology and contribute to the demonstration of safety and viability of the borehole disposal concept.

BOREHOLE DISPOSAL DEMONSTRATION ACTIVITIES

U.S. Deep Borehole Field Test

The U.S. Department of Energy (DOE) and Sandia National Laboratories (SNL) initiated research and development (R&D) for a Deep Borehole Field Test (DBFT) in 2014 to demonstrate and evaluate technologies necessary for determining the safety and feasibility of deep borehole disposal (DBD) of HLW (cesium and strontium capsules currently stored at Hanford, WA), without the use of actual radioactive waste [4]. Between 2014 and 2017 significant R&D was performed in support of the following objectives [4]: (1) demonstrate drilling technology and borehole construction to 5,000 m depth in crystalline basement rock with sufficient diameter for cost-effective waste disposal; (2) evaluate the effectiveness, down to 5,000 m depth, of downhole characterization techniques to assess the thermal-hydrologic-chemical-mechanical (THCM) conditions that control waste stability and containment; (3) evaluate package and seal materials at representative temperature, pressure, salinity, and geochemical conditions; (4) develop and test engineering methods for test package loading, shielded surface operations, and test package emplacement and retrieval; (5) develop and test seal designs and seal emplacement methods; and (6) demonstrate pre-closure and post-closure safety.

The plan for the DBFT included siting and drilling two 5,000 m deep boreholes into crystalline basement rock in a geologically stable continental location in the U.S.: (1) an initial Characterization Borehole (CB), with approximately an 8.5-in (0.22 m) bottom-hole diameter, to facilitate examination of downhole scientific testing methods; and (2) a subsequent Field Test Borehole (FTB), with approximately a 17-in (0.43 m) bottom-hole diameter, to facilitate proof-of-concept of engineering activities using surrogate test packages [4].

Two Requests for Proposal (RFPs) were initiated by the DOE to identify potential sites for the DBFT. In response to the first RFP [8], a contract was awarded in January 2016, to a team led by Battelle Memorial Institute which included a proposed test site in Pierce County, North Dakota. After efforts to acquire both the initial test site in North Dakota and an alternative proposed site in Spink County, South Dakota were unsuccessful, activities were suspended [9].

The experiences in Pierce County, North Dakota and Spink County, South Dakota highlighted the importance of public engagement and support for the DBFT, and that relevant levels of government and other public stakeholders should be involved from the beginning [9]. Using these lessons learned, DOE issued a new RFP [10] which emphasized local, state, and tribal (if applicable) government engagement, as well as public and other stakeholder involvement ahead of proposal submittals and throughout the contract execution phases. The new RFP also allowed for multiple initial awards and multiple phases of contract execution, during which down-selects could be made based on contractor team performance and success with local community acceptance, and to ultimately have one contractor team actually execute the DBFT and drill the Characterization Borehole. In response to the second RFP, four contract awards were announced in December 2016: AECOM for a proposed site in Pecos County, Texas; ENERCON for a proposed site in Quay County, New Mexico; RESPEC for a proposed site in Haakon County, South Dakota; and TerranearPMC for a proposed site in Otero County, New Mexico [9].

Public engagement efforts were initiated by these teams in early 2017, and were positively received in at least one of the proposed communities, but in May 2017 it was announced that "Due to changes in budget priorities, the Department of Energy does not intend to continue supporting the Deep Borehole Field Test (DBFT) project and has initiated a process to effectively end the project immediately" [11].

Despite the termination of the project prior to drilling of either the CB or FTB, R&D activities were performed to advance the state of knowledge for siting guidelines [2], conceptual design and pre-closure operations [12, 13], downhole characterization and testing strategy [14], and pre-closure and post-closure safety assessments [2, 4].

Australia

CSIRO (Commonwealth Scientific and Industrial Research Organisation) – Australia's National Science Agency, ANSTO (Australian Nuclear Science and Technology Organisation), and SNL have created an international partnership to work towards the execution of a full-scale borehole disposal research, development, and demonstration (RD&D) project in Australia [15, 16].

The goal of the RD&D project is to demonstrate the technical feasibility and the long-term safety of vertical borehole disposal as a potential solution for long-lived ILW in Australia. The RD&D activities include (1) a plan to demonstrate surface handling and full-scale field testing of waste and seal emplacement capabilities in a demonstration borehole with a nominal diameter of 27.5-in (0.7 m) and a depth of 2,000 m, and (2) basic research supporting the development of pre- and post-closure safety assessments and an overall safety case [16].

The preliminary design of a deep vertical borehole concept for disposal of Australia's long-lived ILW has focused on the waste that will likely have the highest concentration of long-lived radionuclides, specifically, the vitrified waste from the reprocessing of research reactor fuel from ANSTO. This waste stream will produce an estimated 100 stainless canisters of CSD-U (Conteneurs Standards de Déchets Vitrifiés/CSD-U: verres UMo) [16]. The total expected volume of CSD-U waste (approximately 20 m^3) represents less than 1% of the total estimated ILW volume generated by ANSTO (about 3,060 m^3) [16].

Other waste streams that may require deep borehole disposal include Synroc wastes (about 150 m^3) from the treatment of liquid waste streams from Mo-99 production and spent uranium filter cups from Mo-99 production (between ~10 - 20 m^3, depending on the conditioning method) [16, 17]. The volumes of these waste streams are estimated to be less than for ILW waste streams with a much smaller activity concentration of long-lived radionuclides; therefore, shallower disposal in silo-type or intermediate-depth mined facilities may be possible.

The RD&D activities are designed to demonstrate that a deep disposal borehole can be constructed, waste can be emplaced, and the borehole can be sealed in a manner that meets operational (worker safety) and long-term (public safety) requirements, while being cost-effective.

At this early stage, no site or host rock type has been selected. To facilitate the design of a deep disposal borehole, a generic workflow was developed that considers all key parameters that influence the final design. The workflow included the following parameters: rock type (crystalline, clay, salt), disposal canister diameter, borehole casing requirement, and minimal annular gap between disposal canister and casing or borehole wall [18].

To support planning for a deep borehole field demonstration in Australia, generic post-closure safety assessments have commenced to evaluate the effect of disposal depth and geological environment on radiological impact, and to identify influential parameters [19, 20]. The assessments also facilitate establishing a modeling framework that, while initially generic, can be gradually refined with site-specific data.

Israel

The Israel Atomic energy Commission (IAEC) is collaborating with SNL, Los Alamos National Laboratory (LANL), and Lawrence Livermore National Laboratory LLNL) to assess borehole disposal of radioactive waste in Israel. With limited geological options for disposal, intermediate-depth borehole disposal (IBD) is being considered in the arid Yamin Plain region of the northeastern Negev desert at depths of several hundred meters below ground surface in the vadose zone. Unlike deep borehole disposal of several kilometers, which relies on emplacement below the depth of recirculating groundwater, the safety case for IBD relies more on the aridity of the vadose zone, and the robustness of the engineered barriers (e.g., canister, seals, backfill materials) in the disposal borehole. [21, 22]

To study the suitability of the Yamin Plain region for borehole disposal, a small-diameter characterization borehole is currently being drilled to retrieve core samples and to better understand the vadose zone geo-mechanical and hydrogeochemical properties and percolation flux [22]. Moreover, a wide range of laboratory geochemical, hydrological, and mechanical studies as well as a new seismic survey are being carried out. The information from the characterization borehole as well as the supplementary laboratory and seismic studies will inform the safety case, and, together with performance assessment analyses, will help to identify key areas of uncertainty and guide future R&D activities aimed at demonstrating the feasibility of the IBD concept in Israel.

European Repository Development Organization

The European Repository Development Organization (ERDO) was originally formed as a working group for studying multinational repositories, and includes waste management organizations from European nations with small inventories of radioactive waste [23].

The ERDO borehole disposal project primarily focuses on whether deep borehole disposal might be a suitable alternative to mined repositories for the SNF, HLW, and long-lived ILW inventories from Croatia, Denmark, The Netherlands, Norway, and Slovenia [6, 24].

A reference borehole and canister design for DBD was selected. The reference borehole is 3,500 m deep and 0.775 m (30.5 in) in diameter. The reference canister has an outer diameter of 0.6 m (23.6 in), which leaves room for casing within the borehole, if needed. The canister design gives sufficient mechanical strength to withstand the pressures at the bottom of the borehole and enough chemical stability to remain intact for at least 1,000 years, which is the potential duration of the heat pulse caused by the decay energy in the waste [6].

A single reference canister design that could accommodate as many of the waste forms from the different countries as possible (e.g., SNF assemblies, reprocessing waste, packages with SNF residues) would have the advantage that (1) all the waste types can be handled by a single borehole design, and (2) the same handling equipment and pre-closure safety assessment assumptions can be used in all cases [6]. On the other hand, it may be cost efficient to implement smaller canisters for the smaller waste forms. A narrower canister design could reduce costs of both canisters and boreholes [6].

The reference design is assumed to be located in crystalline rock. However, that does not rule out the possibility that the concept could be adapted to other types of host rock, such as shale or salt [6]. In addition to the reference design, the ERDO borehole project also evaluated site-evaluation factors, regulatory framework, and cost estimates.

Conclusions from the ERDO borehole project were: (1) DBD is a technologically feasible and potentially cost-efficient solution for SNF, HLW, and long-lived ILW from Croatia, Slovenia, Denmark, The Netherlands, and Norway; (2) a multinational DBD-repository is likely to be more cost-effective than separate national repositories; (3) the natural next step in the development of DBD is a full-scale demonstration of site characterization, drilling, waste emplacement and borehole sealing, combined with development of a comprehensive safety case; and (4) because DBD is a less mature concept than mined repositories, increased adaption to site- and waste-specific characteristics would be beneficial, especially as part of a national or multinational disposal program [6].

Norway

Simultaneous to the ERDO borehole project, Norwegian Nuclear Decommissioning (NND) commissioned several studies of how to dispose of Norwegian radioactive waste [25, 26, 27]. These studies investigate borehole disposal concepts, costs, and feasibility specific to Norway as an alternative to a mined geologic repository.

The studies have led NND to release a Contract Notice for the "development of solutions for disposal of spent fuel and other radioactive waste' and the "development of concept for disposal of spent fuel or other highly radioactive waste in one or more boreholes" [28].

CONCLUSIONS

Recent investigations of borehole disposal of nuclear waste have advanced the state-of-knowledge [2, 4, 13, 14, 15, 16, 25, 26] and have identified that a full-scale field demonstration is a natural next step to increasing confidence in the safety and viability of borehole disposal concepts [1, 5, 6, 7]. Potential field-scale activities associated with borehole disposal projects in Australia, Israel, and Norway have the potential to further advance the technology and contribute to the demonstration of safety and feasibility of pre-closure operations, borehole sealing, and post-closure waste isolation.

ACKNOWLEDGEMENTS

This is Sandia publication SAND2022-xxxxC. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

REFERENCES

1. S. TYSON and T. ZAGAR, "Understanding Deep Borehole Disposal Technology in the context of Spent Fuel and High-Level Radioactive Waste Disposal: History, Status, Opportunities and Challenges", *IFNEC Reliable Nuclear Fuel Services Working Group Webinar*, November 4-5, 2020, International Framework for Nuclear Energy Cooperation (IFNEC) (2020).

2. G. FREEZE, E. STEIN, L. PRICE, R. MACKINNON, and J. TILLMAN, "Deep Borehole Disposal Safety Analysis", FCRD-UFD-2016-000075 Rev. 0, SAND2016-10949R. Sandia National Laboratories, Albuquerque, NM (2016).

3. R.A. MULLER, S. FINSTERLE, J. GRIMSICH, R. BALTZER, E.A. MULLER, J.W. RECTOR, J. PAYER, and J. APPS, "Disposal of High-Level Nuclear Waste in Deep Horizontal Drillholes", *Energies* 12, 2052 (2019).

4. G. FREEZE, E. STEIN, P. BRADY, C. LOPEZ, D. SASSANI, K. TRAVIS, and F. GIBB, "Deep Borehole Disposal Safety Case", SAND2019-1915, Sandia National Laboratories, Albuquerque, NM (2019).

5. G. FREEZE, D. SASSANI, P.V. BRADY, E. HARDIN, and D. MALLANTS, "The Need for a Borehole Disposal Field Test for Operations and Emplacement", SAND2021-0196C, *WM2021 Conference Proceedings*, Phoenix, AZ, March 7-11, 2021, Waste Management Symposia (2021).

6. H. KRISTIANSEN, "Boreholes as a permanent solution for national inventories of radioactive waste", https://www.erdo.org/app/uploads/2022/06/ERDO-borehole-report-Final.pdf, European Repository Development Organization (ERDO) (2022).

7. P.V. BRADY and G. FREEZE, "Sandia Research and Development on Deep Borehole Disposal of Nuclear Waste", *IFNEC Reliable Nuclear Fuel Services Working Group Webinar*, November 4-5, 2020, International Framework for Nuclear Energy Cooperation (IFNEC) (2020).

8. U.S. DEPARTMENT OF ENERGY (DOE), "Request for Proposal (RFP) – Deep Borehole Field Test: Site and Characterization Borehole Investigations", Solicitation Number DE-SOL-0008071, U.S. Department of Energy Idaho Operations Office, Idaho Falls, ID (2015).

9. T. GUNTER and G. FREEZE, "Deep Borehole Disposal Research in the United States", *WM2017 Conference Proceedings*, Phoenix, Arizona, March 5-9, 2017 Waste Management Symposia (2017).

10. U.S. DEPARTMENT OF ENERGY (DOE), "Request for Proposal (RFP) – Deep Borehole Field Test: Characterization Borehole Investigations", Solicitation Number DE-SOL-0010181, US Department of Energy Idaho Operations Office, Idaho Falls, ID (2016).

11. U.S. DEPARTMENT OF ENERGY (DOE), "Studying the Feasibility of Deep Boreholes", https://www.energy.gov/under-secretary-science-and-energy/articles/studying-feasibility-deep-boreholes, (2017).

12. SANDIA NATIONAL LABORATORIES (SNL), "Deep Borehole Field Test Conceptual Design Report", FCRD-UFD-2016-000070 Rev. 1, SAND2016-10246R, Sandia National Laboratories, Albuquerque, NM (2016).

13. E. HARDIN, A. CLARK, J. SU, and F. PERETZ, "Preclosure Risk Assessment for Deep Borehole Disposal", SAND2019-1827, Sandia National Laboratories, Albuquerque, NM (2019).

14. K.L. KUHLMAN, E.L. HARDIN and M.J. RIGALI, "Deep Borehole Laboratory and Borehole Testing Strategy: Generic Drilling and Testing Plan", SAND2019-1896, Sandia National Laboratories, Albuquerque, NM (2019).

15. D. MALLANTS, T. BONANO, G. FREEZE, P. BRADY, and D. SASSANI, "Borehole Disposal Demonstration Project: Overview & Collaboration Opportunities", *IFNEC Reliable Nuclear Fuel Services Working Group Webinar*, November 4-5, 2020, International Framework for Nuclear Energy Cooperation (IFNEC) (2020).

16. D. MALLANTS, C. DELLE PIANE, D. DEWHURST, C. DOBLIN, J. ENGELHARDT, L. ESTEBAN, M. JOSH, U. KELKA, M. KHANAL, P. SCHAUBS, B. SHEN, J. SHI, F. TILMAN, and C. WILSKE, "A Framework for Streamlining RD&D Activities for Deep Borehole Disposal", *WM2022 Conference Proceedings*, Phoenix, AZ, March 6-10, 2022, Waste Management Symposia (2022).

17. M.W.A. STEWART, E.R. VANCE, S.A. MORICCA, D.R. BREW, C. CHEUNG, T. EDDOWES, and W. BERMUDEZ, "Immobilisation of Higher Activity Wastes from Nuclear Reactor Production of 99Mo", *Sci. Technol. Nucl. Install.* 2013, 1-16 (2013).

18. T. FISHER, H.-J. ENGELHARDT, and D. MALLANTS, "Methodology for Designing Deep Boreholes for Disposal of Radioactive Waste". *WM2022 Conference Proceedings*, Phoenix, AZ, March 6-10, 2022, Waste Management Symposia (2022).

19. D. MALLANTS and Y. BEIRAGHDAR, "Heat Transport in the Near Field of a Deep Vertical Disposal Borehole: Preliminary Performance Assessment", *WM2021 Conference Proceedings*, Phoenix, AZ, March 7-11, 2021, Waste Management Symposia (2021).

20. D. MALLANTS and Y. BEIRAGHDAR, "Radionuclide transport and deep borehole disposal: Preliminary Safety Assessments", *WM2021 Conference Proceedings*, Phoenix, AZ, March 7-11, 2021, Waste Management Symposia (2021).

21. G. FREEZE, D. SASSANI, O. KLEIN-BEN DAVID, R. CALVO, and G. PEER, "Borehole Disposal of Radioactive Waste in Israel", *WM2020 Conference Proceedings*, Phoenix, AZ, March 8-12, 2020, Waste Management Symposia (2020).

22. O. KLEIN-BEN DAVID, G. FREEZE, D. SASSANI, R. CALVO, N. BALABAN, and G. PEER, "Borehole Disposal of Radioactive Waste in Israel", *EGU General Assembly 2022*, Vienna, Austria, May 23-27, 2022, European Geophysical Union (EGU) (2022).

23. H. KRISTIANSEN, "The ERDO Borehole Disposal Project", *IFNEC Reliable Nuclear Fuel Services Working Group Webinar*, November 4-5, 2020, International Framework for Nuclear Energy Cooperation (IFNEC) (2020).

24. DEEP ISOLATION, "Preliminary assessment of a Deep Isolation borehole repository as a disposal option for nuclear waste in the ERDO countries", Deep Isolation EMEA Ltd (2021).

25. B.S. AADNOY and M.B. DUSSEAULT, "Deep Borehole Placement of Radioactive Wastes, A Feasibility Study", Prepared for Norwegian Nuclear Decommissioning (NND).

26. T. FISCHER, H.-J. ENGELHARDT, and T. WANNE, "Deep Borehole Disposal Concept", BGE TEC, Germany and AINS Group, Finland (2020).

27. T. SAANIO, T. SEPPÄLÄ, T. FISCHER, and T. WANNE, "Technical Readiness Level Assessment", AINS Group, Finland and BGE TEC, Germany (2022).

28. NORWEGIAN NUCLEAR DECOMMISSIONING (NND), "Radioactive waste treatment services - Development of solutions for disposal of spent fuel and other radioactive waste, including borehole disposal", Reference Number 361, Contract Notice 2021/S 255-676718, Norwegian Nuclear Decommissioning, Halden, Norway (2021).