Progress towards the demonstration of deep borehole disposal – 22338

Ethan Bates*, Jesse Sloane*, Matt Waples*, John Midgley**, Chris Parker**, Rod Baltzer*, Theodore J. Garrish***
*Deep Isolation Inc., 2001 Addison St, Suite 300 Berkeley, CA 94704
**Deep Isolation EMEA Limited, Northumberland Avenue, Trafalgar Square, London, WC2N 5BW, U.K.
***Deep Borehole Demonstration Center, 2001 Addison St, Suite 300 Berkeley, CA 94704

ABSTRACT

Research in 2022 by Deep Isolation and the University of Sheffield found that four out of five waste management stakeholders would welcome greater international collaboration on deep borehole disposal, with the highest priority being a full-scale, end-to-end demonstration. This paper outlines the high-level objectives, priorities, and governance model for a deep borehole demonstration program being launched in 2023, as a multi-national, public-private partnership response to these research findings.

The paper begins with a review of prior work on deep borehole design and demonstration planning by other institutions such as Sandia National Laboratories (SNL) in the United States and the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia. It continues with the presentation of preliminary demonstration objectives and phases of operation that are emerging from initial discussions among stakeholders and potential partners in the wake of the 2022 research findings.

Finally, the paper describes the governance model established between interested stakeholders to take forward this phased, multi-year demonstration program. An independent, non-profit Deep Borehole Demonstration Center has been set up to carry forward the mission of advancing deep borehole technology through a series of projects funded on a public-private partnership basis. The paper also describes the early actions being taken by Deep Isolation and its private sector partners to initiate the demonstration by advancing the generic operational and long-term safety cases supporting deep borehole disposal. Starting with a test of the canister latching mechanism and lifting operation in early 2023, these projects will grow in scale and complexity and culminate in a full-scale, end-to-end demonstration of deep borehole disposal.

INTRODUCTION

Need for Demonstration

A 12-month stakeholder research project by Deep Isolation and the University of Sheffield, published in March 2022 [1], found that regulators, policymakers and waste management practitioners internationally view deep borehole disposal (DBD) as a significant opportunity for many national radioactive waste management programs. These stakeholders identify the single most important challenge to be addressed ahead of licensed disposal of radioactive waste is an end-to-end demonstration of the technology. Four out of five research participants would welcome greater international collaboration on DBD, with an emphasis on prioritizing an end-to-end technical demonstration of an operational DBD repository.

The need for a DBD demonstration program is further underscored by the growing international interest in deep borehole disposal and the increasing maturity of the technology and its supporting safety case. Within publications and conferences, there has been a convincing articulation of the need for a deep borehole disposal demonstration project, including from experts at SNL, CSIRO [2], the University of Sheffield [3] in the UK, GRS in Germany [4], and the Electric Power Research Institute [5] in the United States. Recent and relevant proposals and configurations of DBD are summarized in Table I.

TABLE I. Overview of recently researched and proposed applications for DBD

Institution Design param.	**Deep Isolation (DI)***	**CSIRO, Australia**	**SNL, 2019**	**SNL, 2011-2015**	**SNL, 2015**	**Germany 2017-2019**	**UK**, U. of Sheffield 2021 [3]**	**Norway 2020 [6]**	**South Korea (Seoul Nat. U.) 2019 [7]**
Waste form(s)	Intact PWR assemblies*	-Vitrified waste, 180 L CSD-U containers [8] -Synroc from Mo-99 production[9]	Cs and Sr capsules [10], [11]	Intact PWR BWR SNF [12], [13]	Vitrified and granular wastes [14]	Vitrified HLW	Vitrified HLW, 150 L containers with overpacks	Research reactor fuel, 0.52 m diameter BSK-R containers	PWR and CANDU rods
Disposal zone borehole diameter	0.48 m	0.66 m, Ref. [15] 0.7 m, Ref.[8]	0.311 m, Ref. [11]	0.432 m, Ref. [16]	0.91 m	0.75 m, Ref. [17]	0.914 m	0.775 m	0.3-0.5 m
Disposal depth	1.0 to 1.5 km	2000 m Ref.[8] 300 or 800 m, Ref. [18]	4.5 km	3 km	2.5 km	1.5-3.5 km, Ref. [17]	3-5 km	1.8-3.5 km	2-3 km
Disposal zone length	1 to 1.5 km	200 m Ref. [15]	300 m	2 km	500 m	2 km [19]	2 km	1.7 km	
Config-uration	Vertical, directional, or horizontal	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical or deviated	Vertical
Host rock	Crystalline basement or argillaceous rock (including shale).	Crystalline basement	Crystalline basement			Crystalline bed rock, clay, salt, or carbonate -clay rock or salt rock provide geological barriers.	Crystalline basement		

*****Deep Isolation has also considered the economic feasibility of disposing of TRIGA fuel, plutonium, and vitrified HLW in client studies.

**U. of Sheffield's work on deep boreholes began more than 25 years ago [20]. Only the most recent concept is included here.

Acronyms: PWR: Pressurized Water Reactor, BWR: Boiling Water Reactor, SNF: Spent Nuclear Fuel, HLW: High-Level Waste, ILW: Intermediate-Level Radioactive Waste

In the last eight years, performance assessments and publications by Massachusetts Institute of Technology [21], Deep Isolation [22], and CSIRO [18] aligned to conclude that disposal of intermediate and high-level wastes at "medium" [23] or "intermediate" [2] (<2 km) depths could provide a more optimal balance of technical feasibility and long-term safety. Deep Isolation's papers on vertical [22] and horizontal [24], [25] boreholes containing PWR spent nuclear fuel confirmed that adequate safety could be achieved at a depth of 1.5 km in crystalline and shale host rock geologies. More recently, CSIRO's performance assessments suggested that sufficient long-term isolation of radionuclides could be achieved with a vertical borehole drilled as shallow as 300 m [18] for vitrified intermediate-level waste (ILW) produced from reprocessing research reactor fuel. SNL has also acknowledged that low-level waste and sealed sources can be disposed in shallow boreholes (~hundreds of meters) while ILW and high-level waste (HLW) could be disposed at a depth of <2000 meters [2], [11], although 2 km is still considered an approximate minimum depth for SNF disposal [2]. Thus, the modern, medium/intermediate-depth variants of DBD may not expand site availability[1] and options as much as the early "very deep" concepts at 4 km or more. However, shallower applications would provide deployment time frame benefits, requiring a less costly demonstration while enabling a competitive advantage for DBD over mined repositories which have relatively high construction and operational costs for excavation and establishing underground infrastructure [2].

Technical feasibility is also driven by the diameter of the disposal zone. A large disposal zone diameter is desirable to allow for greater capacity and, more importantly, to accommodate a greater variety of waste forms and geometries. Table I and other references [27] show that current international proposals and opportunities for deep boreholes (Australia, UK, Germany, Norway) center around relatively large vitrified waste forms and packages, which require borehole diameters of 0.66-0.9 m considered to be at the edge of current drilling capabilities[2]. In Germany, it is stated [4] that vitrified waste canisters are unlikely to be changed or reconditioned, creating a strict limitation on the borehole diameter. Furthermore, it should be noted that the difficulty of recovering waste[3] from boreholes in the future [27] is seen as a primary barrier to DBD progress in Germany, where a recovery period of 500 years is required according to the German Site Selection Act of 2017 [4].

DESCRIPTION

Review of Prior Calls for Deep Borehole Demonstration

SNL's prior work on a demonstration borehole plan is extensive and provides a useful starting point and framework for planning future demonstrations. For SNL's demonstration, an important site selection requirement was that at least 3 km of the borehole must be in the crystalline basement for a borehole drilled to 5 km total depth. SNL implemented a decision analysis framework to rank and identify priorities for demonstration tests in terms of the importance of the test to borehole performance assessment and its relative maturity [29]. The associated plans [30], [31] and specifications [16] cover the entire set of operations (not just those that are considered novel in terms of deep borehole disposal).

CSIRO, the Australian Nuclear Science and Technology Organization (ANSTO), and SNL have collaborated to plan a borehole demonstration [2] with slightly modified objectives and scope compared to SNL's previously discussed demonstration program. CSIRO's reference design for a borehole is a 0.7- m diameter, 2000 m deep demonstration [2] An earlier summary paper makes a call for a demonstration to specifically address the following items:

- Several iterations of the operational and post-closure safety cases
- Site characterization techniques
- Comparative economic analysis between borehole disposal and mined repositories

---

[1] There has not yet been a quantitative assessment of how much site availability increases as a function of repository depth; however, deeper host rocks present increasingly suitable conditions for waste disposal (e.g., reduced permeability [26], longer pore fluid residence times [21], and longer transport distance). All other things being equal, for a given set of sites, a larger fraction would present suitable conditions for isolation of radionuclides as the design limit for the repository depth is increased.

[2] A comprehensive review of drilling experience and DBD concluded that a 0.750 m diameter vertical disposal zone case at 2 km [28] represents the envelope of currently available technology.

[3] A 2019 UK review of DBD stated [27], "Retrievability is diametrically counter to the concept of DBD, which aims at the maximum isolation possible by specifically making it practically impossible to retrieve waste once a borehole is sealed and decommissioned."

- Surface handling and emplacement demonstration using surrogate waste canisters in a shallow borehole to assess surface handling/emplacement/tracking protocols at the field scale. This type of field-scale test would advance the protocols and implementation of the technology and contribute to the demonstration of safety and viability of the borehole disposal concept [2].

In a 2020 meeting of the Reliable Nuclear Fuel Services Working Group of the International Framework for Nuclear Energy Cooperation (IFNEC), presenters concluded [32] that a DBD test will need to demonstrate that radioactive waste can be safely disposed of in a borehole by:

- drilling and completing a borehole to target depths at the required diameter
- sufficiently characterizing the geological formations surrounding the borehole
- surface handling of non-radioactive waste (i.e., “cold”) canisters and subsequent waste canister emplacement workflow (i.e., with all necessary methodology for radioactive materials handling) and technology under controlled conditions (initially at the ‘engineering’ scale, but ultimately at full scale)
- safely retrieving non-radioactive waste canisters evaluating the plugging and sealing materials installation processes
- undertaking total system performance assessments showing conformity with applicable radiological safety criteria.

DISCUSSION

Following publication of the research identifying demonstration as the top priority for DBD collaboration between international waste management stakeholders [1], dialogue between stakeholders on the best way of addressing this need was facilitated through an evolving consultation document [33]. This resulted in interested stakeholders coming together to establish an independent, collaborative, multi-stakeholder driven, non-profit organization: the Deep Borehole Demonstration Center (“the Center”). The Center was established in the State of Texas on 1 December 2022, with an independent Board of Directors with members drawn from the public and private sectors, and will host progressively advanced DBD experiments and tests, ultimately leading up to an end-to-end (non-radioactive) demonstration of the deep borehole disposal technology. Below, this paper outlines the planned objectives and phasing of this demonstration and then describes in more detail the Center’s governance and funding model.

Demonstration Objectives and Assumptions

The primary objective of the non-radioactive demonstration is to advance the generic safety case for deep borehole disposal and the technology readiness of its various components by executing the operations in conditions that are as similar as possible to those for active implementation. Execution of the proposed DBD demonstration program will be based on the following high-level assumptions:

- The proposed demonstration program will be carried out at a dedicated demonstration facility in Texas. Engagement with state and local stakeholders near any testing facility will be required during planning of the demonstration.

- No radioactive material will be placed in the demonstration canisters.

- The demonstration facility will address priorities identified in the preliminary [34] and future revisions to the technology readiness assessment.

- Retrievability requirements have not been determined, but potential customers have said retrievability is a key aspect for deep borehole disposal. Current repository specifications and the concept of operations [35] do not envision retrieval of canisters after the repository is sealed as being within the design basis. However, there could be significant value to demonstrating aspects of retrieval prior to sealing (e.g., validation of borehole stability models), so it will be included in the demonstration.

- Throughout the process, the Deep Borehole Demonstration Center will provide key results of these demonstration activities to stakeholders, publish results in scientific papers, and invite international peer review to support verification of the demonstration results.

Largely following the sequence and processes identified in a prior technology readiness assessment [34], the borehole demonstration should address the range of DBD processes shown in TABLE II.

TABLE II. Processes of DBD operation to be addressed by the demonstration

Process #	**Name**	**Description**
0	Site and borehole characterization	Drill characterization hole(s), collect data, and develop numerical models to support performance model of a repository.
1	Surface handling demonstration	Demonstrate design basis and accident conditions for handling processes.
2	Drilling	Demonstrate that a borehole can be drilled to specifications required for a repository.
3	Full-scale emplacement and retrieval demonstration	Demonstrate design basis emplacement and retrieval scenarios.
4	Emplacement safety demonstrations	Demonstrate off-normal conditions and accident conditions such as drop and runway tests.
5	Site and borehole characterization via heated canister test	Characterize relevant thermal, hydraulic, mechanical, and chemical properties in the disposal zone and overlying units.
6	Repository closure and environmental impact	Demonstrate closure processes.

Site Characterization Objectives

Deep Isolation is conducting a preliminary assessment of the site characterization techniques to be used at a future candidate repository site. Over the last two decades, drilling and data acquisition have successfully taken place in a wider range of geological settings to meet the needs of increasingly challenging oil and gas scenarios, carbon storage, and long-term retention of fluids and pressures in geothermal applications in relatively large borehole diameters. In general, subsurface activities require very similar data (e.g., porosity and permeability, pressure and temperature, geomechanics, geochemistry, structural data, flow characteristics, etc.) with the differences in projects emphasizing the relative values and interpretation of these data. The methods of acquiring these data are also similar across these applications, with a focus on real-time data acquisition while drilling (cuttings, gas, drilling data, logging while drilling), and coring activities across lithologic boundaries. Furthermore, the shared objectives across these applications include accurately identifying pore scale rock attributes for log calibration, acquiring in-situ fluid samples and minerology, and executing wireline logging programs for a suite of data acquisition meeting the project’s more specific geological data needs.

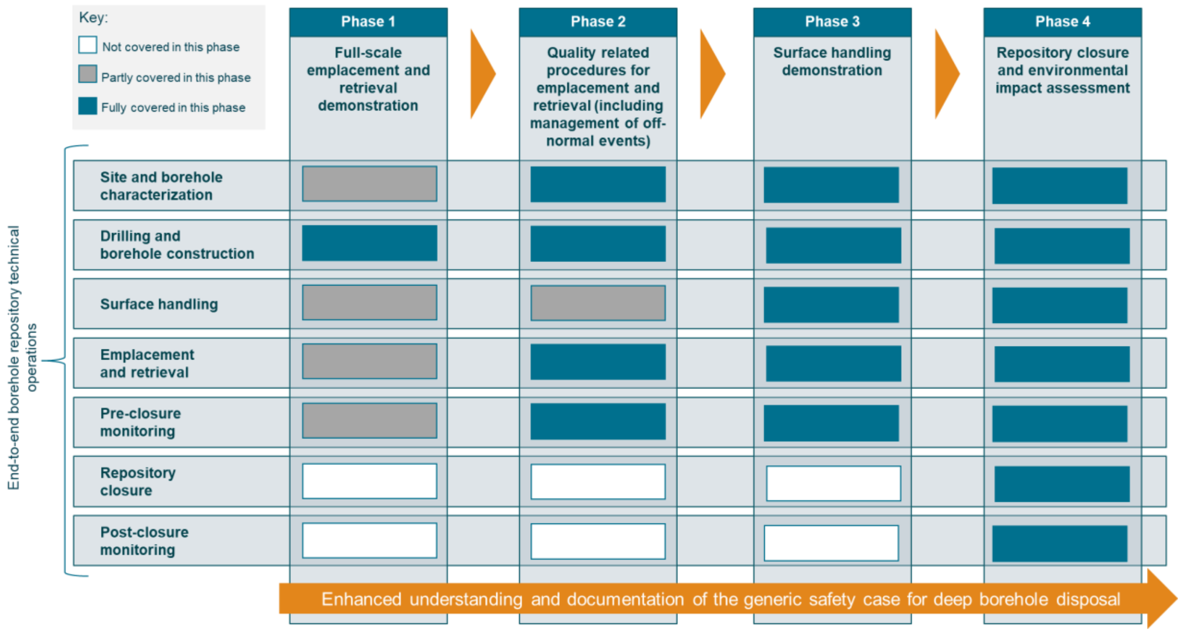
These initial findings suggest that many of the proposed site characterization techniques will already be included as part of standard drilling processes or have been demonstrated in other applications at full scale, and thus there may be less technical value in demonstrating these methods compared to other objectives. The techniques unique to a borehole repository and thus more valuable for demonstration are summarized in Table III.

TABLE III. Summary of site characterization methods to be prioritized in deep borehole demonstration

Site Characterization Method	Description	Importance to Safety
Drill cuttings lithology log	Rock type and mineralogical and textural characteristics.	High importance to provide geology and engineering data. Often required for safety when drilling deep boreholes.
Intermittent and sidewall coring (oriented coring)	Intact samples of the host rock for hydrological, thermal, mechanical, and chemical analyses.	Essential to understand properties and conditions around emplacement zone.
Wireline log data and flow-testing	Determine rock properties and hydraulic flow.	High importance.
Drill stem pump tests: pressure, permeability, water chemistry	Host rock permeability and pore pressures are measured by pumping fluids.	High importance in some areas of the borehole.
Fluid samples from packer testing	Fluid samples are analyzed for chemical composition.	Essential for high quality water samples for isotope analysis (to determine residence time), pH, etc.
Waste canister mockup heater test	A heated and instrumented canister is emplaced and used to determine thermal properties and response of the host rock.	Low-medium importance. Current performance assessments (for 30 year aged fuel) suggest that local perturbations due to heat-up will not have significant impacts on performance[22], [24]. Reducing cooling periods or certain waste forms may introduce new phenomena (boiling, thermo-mechanical effects).

Phased Approach

Fig. 1 shows a preliminary outline of the proposed demonstration elements with sequencing that could be adapted according to partner, investor, and funding constraints. Based on current discussions with stakeholders and Deep Isolation’s technology readiness assessment [34], this phased approach prioritizes an initial demonstration phase that includes drilling a full-sized hole, emplacing a full-sized waste canister, and retrieving that canister.



Key:
☐ Not covered in this phase
▨ Partly covered in this phase
■ Fully covered in this phase

End-to-end borehole repository technical operations

	Phase 1 Full-scale emplacement and retrieval demonstration	Phase 2 Quality related procedures for emplacement and retrieval (including management of off-normal events)	Phase 3 Surface handling demonstration	Phase 4 Repository closure and environmental impact assessment
Site and borehole characterization	▨	■	■	■
Drilling and borehole construction	■	■	■	■
Surface handling	▨	▨	■	■
Emplacement and retrieval	▨	■	■	■
Pre-closure monitoring	▨	■	■	■
Repository closure	☐	☐	☐	■
Post-closure monitoring	☐	☐	☐	■

Enhanced understanding and documentation of the generic safety case for deep borehole disposal

Fig. 1. Proposed demonstration phases by priority

The phasing shown has been broadly validated with international waste management organizations through a consultation document [33] – although stakeholder views vary on whether the priority for an initial borehole in Phase 1 should be:

1. A horizontal disposal section, sized for disposal of PWR spent fuel; or
2. A larger-diameter vertical disposal section, sized for larger vitrified HLW canisters.

Against this context, two projects are currently envisaged during Phase 1:

- **Project 1.0:** a foundational project, lasting about nine months, aimed at finalizing the specifications of the initial borehole, and establishing all the technical, industrial, and regulatory infrastructure needed to construct and deliver a borehole demonstration. Project 1.0 will also include a range of supporting technical efforts and intermediate demonstrations led and funded by Deep Isolation, including:

    - **Canister handling:** Demonstration of the canister lifting operation and latching mechanism using a full-scale mockup canister, currently scheduled for February 2023.
    - **Features, events, and processes (FEPs) analysis**: FEPs analysis for borehole concepts in a wider range of geologies to expand applicability and advance the generic long-term safety case of DBD [36].
    - **Operational safety:** Documentation of the sequence of operations for canister transportation and emplacement and establishing the underlying generic operational safety case for a DBD facility.

- **Project 1.1:** with consultation with Program Sponsors, the Center's Advisory Committee, and other interested sponsors, specifications and plans for the initial borehole drilling and emplacement demonstration will be finalized. With funding commitments for this next step, Project 1.1 will commence with the finalization of the borehole and wellhead design, drilling and construction of a full-scale test borehole, and delivering and evaluating emplacement and retrieval operations, for example, using the canister designs and sequence of operations evaluated in Project 1.0.

Governance Structure and Guiding Principles

To achieve the objectives set forth above, the Deep Borehole Demonstration Center has been established to pursue a single purpose, which is:

- To accelerate the global deployment of deep borehole disposal as a solution for the safe geological disposal of radioactive waste, through non-radioactive demonstration, evaluation and dissemination of learnings for borehole disposal technologies and processes, and the use of these learnings to further the generic safety case for borehole disposal.

The Deep Borehole Demonstration Center will be governed according to six key principles, derived from stakeholder feedback and a review of successful governance models implemented by underground research laboratories [37], such as Äspö and Grimsel:

1. **Transparency and Inclusion:** The demonstration program will be managed by a special-purpose, non-profit organization with a Board of Directors that does not comprise a majority of any one organization. The Center is subject to external scrutiny and recommendations made by an independent Advisory Committee bringing together representatives of all key stakeholder groups.
2. **Community Engagement:** The Center will work closely with the local community to maximize local economic impact from this non-radioactive demonstration facility and to ensure ongoing consent, including through community representation on the Advisory Committee.
3. **Scientific Excellence:** Outcome and performance data from the demonstration program will be published and subject to international peer review.
4. **A Long-Term, Phased, and Prioritized Approach:** The aim will be to operate an ongoing facility to test cost and safety models through live demonstrations and experiments. Priorities will be agreed upon in consultation with stakeholders as the Center develops its multi-year work program over the coming months.
5. **Public Private Partnership:** The Center will seek funding from both the private sector and public sector - recognizing that the latter will take longer to mobilize.
6. **Early Results:** Deep Isolation and its private sector partners are committed to early action to kick-start the demonstration.

An overview of the structure that has been developed through stakeholder consultations in order to implement the above principles is shown in Fig. 2.

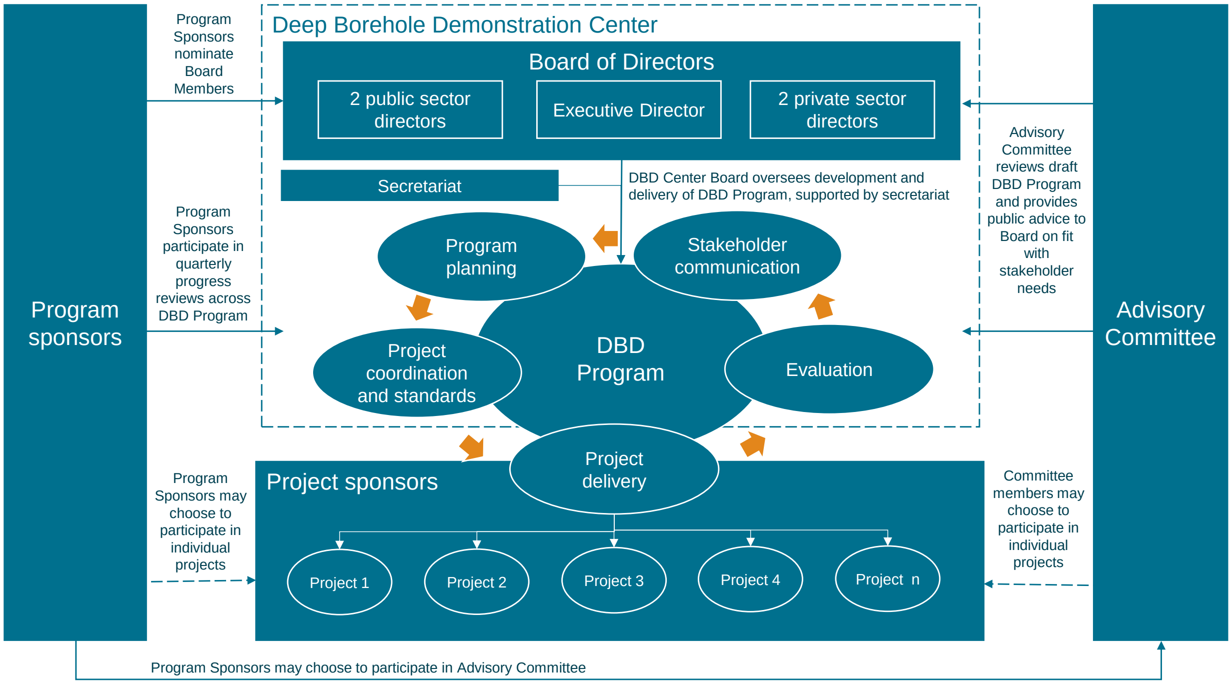


Fig. 2. Governance structure for the Deep Borehole Demonstration Center

Progress in Establishing the Deep Borehole Demonstration Center

The Deep Borehole Demonstration Center was established as a legal entity in the State of Texas, U.S.A. on 1 December 2022. The Board of Directors consists of non-executive directors drawn from the public and private sectors, and an Executive Director with a track record of public service at senior levels within the US Department of Energy. The necessary lease to host this non-radioactive demonstration has been secured and community engagement is ongoing. Initial members of the Center include organizations representing waste disposal interests in nine countries, from both the public and private sectors, and the Center continues actively to recruit more Program Sponsors. Deep Isolation is committing resources to take forward the foundational ‘Project 1.0’ during 2023 – which includes the first onsite testing event in February 2023 (focused on testing the canister-latching mechanism using a full-scale mockup disposal canister). In February 2023, the UK government’s Department for Energy Security and Net Zero announced that it was providing grant support to advance Deep Isolation’s disposal canister to a technology readiness level (TRL) of 7 in partnership with the Nuclear Advanced Manufacturing Research Center, with laboratory testing of the canister in the UK and field testing at the Deep Borehole Demonstration Center [38].

Regarding the canister design, in the past year it has been refined for compatibility with standard lifting equipment, manufacturability, and operational efficiency. The new lift adapter utilizes standard profiles which interface with existing pressure-actuated lifting equipment (“GS” connector) that does not require rotation to engage or disengage with the lift adapter. The bottom plate and shell thicknesses were also reduced to align with more commercially standard dimensions without affecting the conclusions of existing structural, thermal, shielding, or criticality safety analyses. Lastly, chamfers were introduced in the closure lid and shell to facilitate remote insertion of the closure lid in a water pool environment. Additional detail on the most recent progress in deep borehole canister design is contained in [39].

CONCLUSIONS

Deep boreholes could offer new disposal pathways and strategies, enhanced levels of long-term safety, and significant siting and cost benefits over existing technologies. The need for demonstration of deep borehole technology to address technical uncertainties has been articulated internationally for many years, and in 2022 was highlighted as a top priority for stakeholders in the international waste management community. This paper reviews the progress that stakeholders across the international community have made in the last year in terms of establishing priorities, a phased approach, and a governance structure for the Deep Borehole Demonstration Center that will address this need.

REFERENCES

[1] C. Parker, F. Brundish, B. Madru, J. Mathieson, and N. Chapman, "Implementing Deep Borehole Disposal: Study of International Stakeholder Views from Regulatory, Policy & WMO Communities," in *WM2022*, Phoenix Arizona, Mar. 2022.

[2] G. Freeze, D. Sassani, P. V. Brady, E. Hardin, and D. Mallants, "The Need for a Borehole Disposal Field Test for Operations and Emplacement," in *WM 2021*, Phoenix, Arizona, Mar. 2021.

[3] F. G. Gibb and A. J. Beswick, "A deep borehole disposal solution for the UK's high-level radioactive waste," *Proc. Inst. Civ. Eng.-Energy*, pp. 1–19, 2021.

[4] G. Bracke, W. Kudla, and T. Rosenzweig, "Status of Deep Borehole Disposal of High-Level Radioactive Waste in Germany," *Energies*, vol. 12, no. 13, p. 2580, 2019.

[5] A. Sowder, R. McCullum, and V. Kindfuller, "Why demonstration of a deep borehole disposal concept matters to the nuclear industry," presented at the Proceedings of the International High-Level Radioactive Waste Management Conference, 2015.

[6] F. Tillman, J. Engelhardt, and T. Wanne, "Deep Borehole Disposal Concept," AINS Group, Sep. 2020.

[7] B. Jeon, S. Choi, S. Lee, and S. Jeon, "A conceptual study for deep borehole disposal of high level radioactive waste in Korea," *Tunn. Undergr. Space*, vol. 29, no. 2, pp. 75–88, 2019.

[8] D. Mallants *et al.*, "Deep borehole disposal of intermediate-level waste: progress from Australia's RD&D project," in *Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting*, Aug. 2021.

[9] M. W. A. Stewart *et al.*, "Immobilisation of Higher Activity Wastes from Nuclear Reactor Production of 99Mo," *Sci. Technol. Nucl. Install.*, vol. 2013, p. 926026, Dec. 2013, doi: 10.1155/2013/926026.

[10] G. Freeze *et al.*, "Generic Deep Geologic Disposal Safety Case," *SAND2013-0974P*, p. 372, 2013.

[11] G. A. Freeze, E. Stein, and P. V. Brady, "Post-Closure Performance Assessment for Deep Borehole Disposal of Cs/Sr Capsules," *Energies*, vol. 12, no. 10, 2019.

[12] E. Hardin, J. R. Cochran, and P. V. Brady, "Deep Borehole Disposal for Countries with Small Nuclear Programs," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2017.

[13] 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 Natl. Lab. Albuq. NM*, 2011.

[14] M. J. Rigali, S. Pye, and E. Hardin, "Large Diameter Deep Borehole (LDDB) Disposal Design Option for Vitrified High-Level Waste (HLW) and Granular Wastes.," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2016.

[15] D. Mallants and Y. Beiraghdar, "Heat Transport in the Near Field of a Deep Vertical Disposal Borehole: Preliminary Performance Assessment–21195".

[16] E. Hardin, "Deep Borehole Field Test Specifications.," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2015.

[17] G. Bracke, F. Charlier, A. Liebscher, F. Schilling, and T. Röckel, "Does Deep Borehole Disposal of HLRW has a Chance in Germany?," *Atw Atomwirtsch.*, vol. 62, p. 46, Jan. 2017.

[18] D. Mallants and Y. Beiraghdar, “Radionuclide transport and deep borehole disposal: preliminary safety assessments,” in *WM2021*, Phoenix, Arizona, Mar. 2021.

[19] G. Bracke, F. Charlier, A. Liebscher, F. R. Schilling, and T. Röckel, “About the Possibility of Disposal of HLRW in Deep Boreholes in Germany,” *Geosciences*, vol. 7, no. 3, 2017, doi: 10.3390/geosciences7030058.

[20] N. Chapman and F. Gibb, “A Truly Final Waste Management Solution: Is Very Deep Borehole Disposal a Realistic Option for High-Level Waste or Fissile Materials?,” *Radwaste Solut.*, vol. 10, pp. 26–37, Jul. 2003.

[21] E. A. Bates, “Optimization of deep boreholes for disposal of high-level nuclear waste,” Ph.D. Thesis, Massachusetts Institute of Technology, 2015.

[22] S. Finsterle, R. A. Muller, J. Grimsich, E. A. Bates, and J. Midgley, “Post-Closure Safety Analysis of Nuclear Waste Disposal in Deep Vertical Boreholes,” *Energies*, vol. 14, no. 19, 2021, doi: 10.3390/en14196356.

[23] D. Mallants, K. Travis, N. Chapman, P. V. Brady, and H. Griffiths, “The State of the Science and Technology in Deep Borehole Disposal of Nuclear Waste,” *Energies*, vol. 13, no. 4, 2020, doi: 10.3390/en13040833.

[24] S. Finsterle, C. Cooper, R. A. Muller, J. Grimsich, and J. Apps, “Sealing of a Deep Horizontal Borehole Repository for Nuclear Waste,” *Energies*, vol. 14, no. 1, p. 91, 2021.

[25] R. A. Muller *et al.*, “Disposal of high-level nuclear waste in deep horizontal drillholes,” *Energies*, vol. 12, no. 11, p. 2052, 2019.

[26] P. Achtziger-Zupančič, S. Loew, and G. Mariéthoz, “A new global database to improve predictions of permeability distribution in crystalline rocks at site scale,” *J. Geophys. Res. Solid Earth*, vol. 122, no. 5, pp. 3513–3539, May 2017, doi: 10.1002/2017JB014106.

[27] N. A. Chapman, “Who Might Be Interested in a Deep Borehole Disposal Facility for Their Radioactive Waste?,” *Energies*, vol. 12, no. 8, p. 1542, 2019.

[28] J. Beswick, “Status of technology for deep borehole disposal,” *Rep. NDA Contract NP*, vol. 1185, 2008.

[29] B. W. Arnold *et al.*, “Deep Borehole Disposal Research: Demonstration Site Selection Guidelines Borehole Seals Design and RD&D Needs.,” Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2013.

[30] K. L. Kuhlman *et al.*, “Conceptual Design and Requirements for Characterization and Field Test Boreholes: Deep Borehole Field Test,” Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); Lawrence …, 2015.

[31] K. L. Kuhlman, E. Hardin, and M. J. Rigali, “Deep Borehole Laboratory and Borehole Testing Strategy: Generic Drilling and Testing Plan.,” United States, Feb. 2019. doi: 10.2172/1497220.

[32] 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,” presented at the IFNEC Reliable Nuclear Fuel Services Working Group, Nov. 04, 2020.

[33] C. Parker and E. Bates, “Deep Borehole Demonstration Center: A consultation paper,” Deep Isolation, Version 3.1, May 2022.

[34] E. Bates, M. Frei, J. Midgley, J. Mathieson, and R. Baltzer, “Preliminary Technology Readiness Assessment of Deep Borehole Disposal,” presented at the WM2022, Phoenix, Arizona, Mar. 2022.

[35] E. Bates, “Deep Borehole Concept of Operations (Rev. 1),” DI-SE-01 (Rev. 1), Oct. 2021.

[36] E. Bates and J. Midgley, “Features, Events, and Processes Prioritization for Deep Borehole Disposal Concepts in Crystalline Rock and Shale,” in *Proceedings of the ANS Annual Meeting*, Anaheim, CA, Jun. 2022.

[37] R. J. MacKinnon, “The Use of Underground Research Laboratories to Support Repository Development Programs. A Roadmap for the Underground Research Facilities Network.,” Sandia National Laboratories, Albuquerque, NM, SAND2015-9427 607843, Oct. 2015. doi: 10.2172/1225846.

[38] "Deep Isolation awarded grant for nuclear waste disposal canister development in the U.K.," *Deep Isolation Press Release*, Feb. 08, 2023. https://www.deepisolation.com/press/deep-isolation-awarded-grant-for-nuclear-waste-disposalcanister-development-in-the-u-k/

[39] M. Waples *et al.*, "Progress on Canisters for Radioactive Waste Transport, Storage and Disposal in Boreholes," in *WM2023*, Phoenix Arizona, Mar. 2023.