DEEP BOREHOLE DEMONSTRATION CENTER

Strategic Plan

February 2023

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1 Introduction

The Deep Borehole Demonstration Center is a nonprofit organization, founded in December 2022, with a mission to advance Deep Borehole Disposal (DBD) through demonstration of the technology and continued development of the supporting safety case.

This is the Center's Strategic Plan. It is in six main sections:

- Section 1 is this **introduction**
- Section 2 sets out the **context** for our work – including:
  - The global need for deep borehole demonstration
  - The process of research, stakeholder dialogue and international collaboration that led to the creation of the Deep Borehole Demonstration Center in response to that need
- Section 3 describes our **governance model**: our purpose, our guiding principles, and the multinational, public-private-partnership operating model that has been designed to enable high levels of regulatory and public trust in the outcomes from our demonstration program.
- Section 4 provides an **analysis of technology maturity and prior work** in relation to deep borehole demonstration
- Section 5 describes the **Deep Borehole Demonstration Program** – our intentions for a phased, multi-year program of work that builds on prior efforts and analysis and reflects the stakeholder priorities that have emerged from consultation during our foundational phase.
- Section 6 provides further details on **how stakeholders can engage** with the activities of the Deep Borehole Demonstration Center.

2 Context

2.1 Deep borehole disposal: a maturing solution to a global problem

Since the EBR-I reactor in Idaho generated the first nuclear-powered electricity in 1951, more than 500 additional nuclear power plants have followed. Together, these contribute over 10% of the world's power, and in the United States for example, nuclear power provides more than 50% of the nation's carbon-free electricity. Looking to the future, the International Energy Agency forecasts that world nuclear capacity will more than double between 2020 and 2050 as part of its central scenario for how the world will achieve net-zero CO_2 emissions across the global energy sector by 2050.

Yet while nuclear power generation has no direct carbon emissions, it also creates waste that can remain hazardous to the environment and human health for thousands of years. We need safe, scalable, permanent solutions for disposal of this waste.

There is clear global consensus – across governments, regulators, scientists and the nuclear industry – that the optimal solution for the long-term disposal of this high-level nuclear waste (HLW) is through deep geological disposal. As the International Atomic Energy Authority puts it [1]:

> "There is presently a broad consensus among technical experts that the preferred method of ensuring long term safety for HLW is isolation in a deep geological disposal facility. Geological disposal facilities for long lived waste, if properly sited and constructed, provide passive, multibarrier isolation of radioactive materials. Emplacement in carefully engineered structures buried deep within suitable rock formations provides the long-term stability typical of a stable geological environment. At depths of several hundred metres, in a tectonically stable region, processes that could disrupt the disposal facility are so slow that the deep rock and groundwater system remain practically unchanged over hundreds of thousands or even millions of years."

While there are many countries that have yet to decide or publish long-term policies for disposal of high-level nuclear waste, every country that has identified a complete solution included deep geological disposal. However, relatively few countries at present have clear pathways for implementing such a geologic disposal facility in a specific site that commands community support. Furthermore, even in countries that have been successful in siting geologic disposal facilities such as Finland and Sweden, the total timescale for deploying the solution has been 60-75 years [2].

That is why there is growing interest in alternative technologies that also have the potential to deliver the safety benefits of geologic disposal, offering communities and policy makers a different option to a mined disposal facility at a potentially faster rate of deployment [3]. In particular, there is 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 Sandia National Laboratories (SNL), Commonwealth Scientific and Industrial Research Organisation (CSIRO) [4], the University of Sheffield [5] in the UK, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) in Germany [6], and the Electric Power Research Institute [7] 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 [5]	**Norway 2020** [8]	**South Korea** (Seoul Nat. U.) 2019 [9]
Waste form(s)	Intact PWR assemblies*	-Vitrified waste, 180 L CSD-U containers [10] -Synroc from Mo-99 production[11]	Cs and Sr capsules [12], [13]	Intact PWR BWR SNF [14], [15]	Vitrified and granular wastes [16]	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. [17] 0.7 m, Ref.[10]	0.311 m, Ref. [13]	0.432 m, Ref. [18]	0.91 m	0.75 m, Ref. [19]	0.914 m	0.775 m	0.3-0.5 m
Disposal depth	1.0 to 1.5 km	2000 m Ref.[10] 300 or 800 m, Ref. [20]	4.5 km	3 km	2.5 km	1.5- 3.5 km, Ref. [19]	3-5 km	1.8-3.5 km	2-3 km
Disposal zone length	1 to 1.5 km	200 m Ref. [17]	300 m	2 km	500 m	2 km [21]	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 [22]. 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

The technical feasibility of the deep borehole concept is limited by the proposed combination of depth and borehole diameter [23]. The earliest DBD concepts for spent nuclear fuel (SNF) assemblies emerged more than 30 to 40 years ago from the United States [24] and Sweden's SKB [25] who proposed "very deep" depths (2-5 km) and diameters that were considered at the edge (or even beyond) technical feasibility at the time. The primary advantages of operating at greater depths and alternative configurations (i.e., horizontal) are seen [22], [26] as increased availability of sites satisfying isolation criteria at great depths >3 km for:

- Reduced site characterization costs, due to lower sensitivity of the safety case to details of fracture geometry [27] and
- Reduced performance requirements and development costs and timeframes for engineered barriers such as canisters [25], [26], which have little to no safety significance in DBD (i.e., the canister can be assumed to fail instantaneously) [28].

Furthermore, given the wider availability of siting options [25], [26], this could allow for the colocation of a repository within the boundaries of an existing nuclear site where waste is stored [27], [29].

In the last eight years, performance assessments and statements by Massachusetts Institute of Technology (MIT) [30], Deep Isolation [31], and CSIRO [20] aligned to conclude that disposal of intermediate and high-level wastes at “medium” [32] or “intermediate” [4] (<2 km) depths could provide a more optimal balance of technical feasibility and long-term safety. Deep Isolation's papers on vertical [31] and horizontal [33], [34] boreholes containing PWR SNF confirmed that adequate safety could be achieved at a depth of 1.5 km in crystalline and shale host rock geologies, respectively. More recently, CSIRO showed that sufficient long-term isolation of radionuclides could be achieved with a vertical borehole drilled as shallow as 300 m [20] for vitrified Intermediate-Level Radioactive 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 [4], [13], although 2 km is still considered an approximate minimum depth for SNF disposal [4]. Thus, the modern, medium/intermediate-depth variants of DBD would not expand site availability[1] and options as much as the early “very deep” concepts. However, shallower applications would provide deployment time frame benefits because they require a less costly demonstration while still enabling a competitive advantage for DBD over mined repositories which have relatively high construction and operational costs for excavation and establishing underground infrastructure [4].

2.2 The need for international collaboration

A 12-month stakeholder research project across eighteen countries by Deep Isolation and the University of Sheffield, published in March 2022 [36], 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 top priorities being:

- **Demonstration:** Establishing an end-to-end technical demonstration of an operational DBD repository
- **Guidance:** Using a demonstration as the focus for international collaboration to develop improved guidance and international consensus around how to demonstrate and validate the safety case for DBD

2.3 Responding to that need: the Deep Borehole Demonstration Center

Following publication of the above research, Deep Isolation initiated a process of dialogue between stakeholders on the best way of addressing this need, including through a series of face-to-face and

[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 [35], longer pore fluid residence times[30], 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.

online discussions with national waste management organizations interested in DBD. Dialogue was facilitated through an evolving consultation document [30].

This resulted in interested stakeholders coming together to establish an independent, collaborative, multi-stakeholder driven, nonprofit 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 comprised of members drawn from the public and private sectors. It 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.

The next sections describe the governance model that has been developed for the Center, and the initial plans and priorities it has developed in consultation with stakeholders.

3 Governance model

3.1 Overview

Stakeholder feedback during the dialogue process described at Section 2.3 above made clear that the objectives and impact of a demonstration program will be achieved best if it is managed by a special purpose vehicle with collaborative, multi-stakeholder governance.

The Deep Borehole Demonstration Center has been established by stakeholders in direct response to that feedback. The Center:

- Has 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.
- Is **independent** and **nonprofit** – and will seek recognition by the US tax authorities as compliant with '501(c)(3)' requirements that guarantee both aspects to the highest standards.
- Has an **independent Advisory Committee** that brings together representatives of the local community, the scientific community and relevant international stakeholders.

3.2 Guiding principles

Based on stakeholder feedback and a review of successful governance models implemented by Underground Research Laboratories such as Äspö and Grimsel, the Center will operate according to six key principles:

1. **Transparency and Inclusion:** The demonstration program will be managed by a special-purpose, non-profit organization with a Board of Directors that is not controlled by any one organization. The Center is subject to external scrutiny and recommendations made by an independent Advisory Committee.
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 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:** Unlike Deep Isolation's initial demonstration of canister emplacement and retrieval in 2018, the aim will not be to deliver a one-time event, but an ongoing facility to test cost and safety models in real-world scenarios. Initial priorities for this are set out in Section 5 below and will be kept under review with stakeholders as the Center develops a multi-year work program over the coming months.

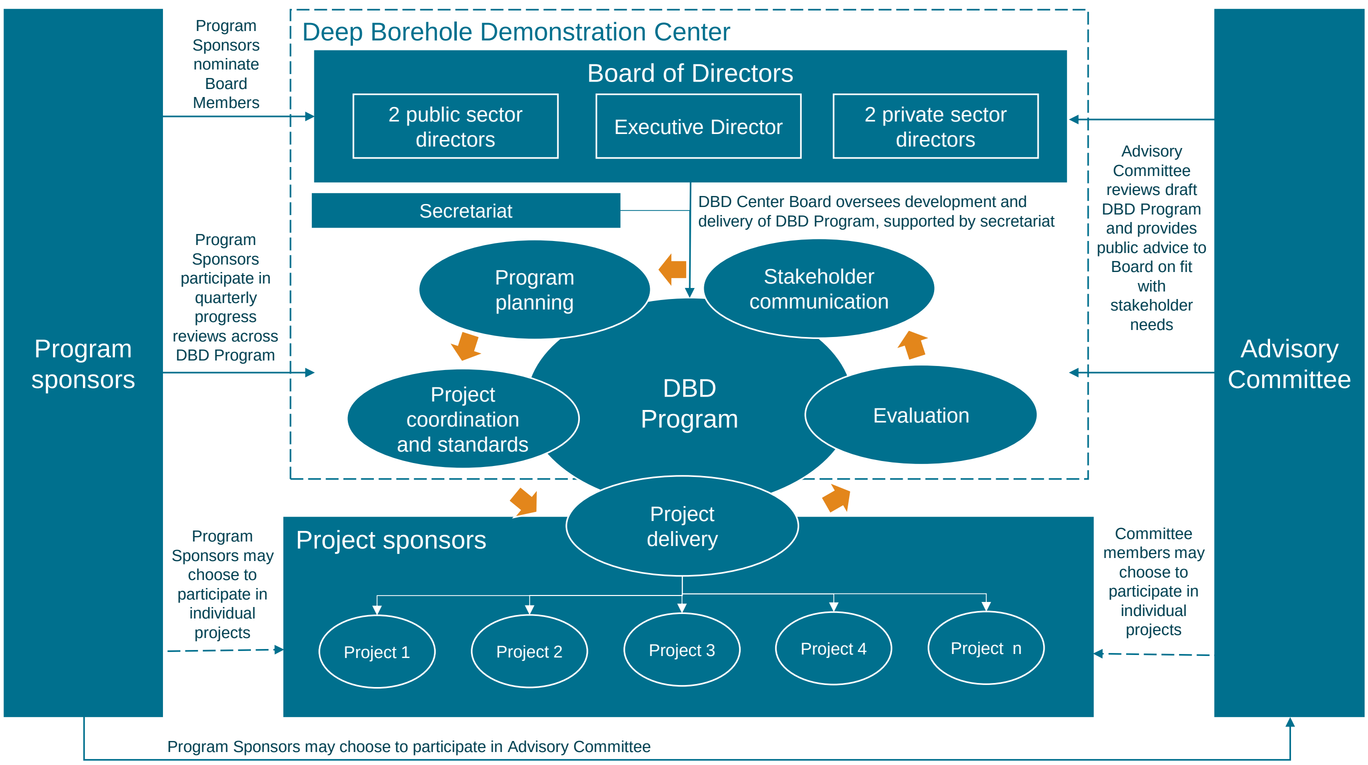
5. **Public Private Partnership:** The Center will seek funding from both the private sector and public sector - recognizing that the latter will take longer to mobilize.

6. **Early Results:** Private sector partners are committed to early action to kick-start the demonstration. Priority actions for an initial 'Project 1.0' to pump-prime the longer-term demonstration program are set out at Section 5.61.

3.3 Governance structure

The Center's governance structure is illustrated below, with each key element then described in more detail.

Figure 1: Governance structure for the Deep Borehole Demonstration Center



3.3.1 Board of Directors

The Board of Directors is accountable for the following:

- **Developing and overseeing delivery of a Deep Borehole Demonstration Program** (see Section 3.5 below) that achieves the purpose of the Deep Borehole Demonstration Center.
- **Ensuring transparent and inclusive governance for the program**, including by publishing updates to and progress reports on the Program every 12 months following consultation with Program Sponsors and the independent Advisory Committee (see Section 3.3.4 below)

- **Ensuring that the Center operates in full compliance** with all its fiscal and regulatory duties as a non-profit organization, ensuring that all revenue to the Center is devoted to pursuit of its purpose.

Reflecting the guiding principle of public-private-partnership, we envision that there should be representatives from both sectors on the board. The initial board directors at the time of the Center's launch are:

- Jitka Mikšová, Head of the RWM Division at the National Radiation Protection Institute (SÚRO), Czech Republic
- Dr. Richard Esposito, R&D Program Manager for Geosciences & Carbon Management at Southern Company
- Liz Muller, CEO of Deep Isolation.

The Board is supported by an Executive Director, who takes the lead in day-to-day development and implementation of the Deep Borehole Demonstration Program (see Section 3.3.3) and works with partners to scope and secure funding for future Demonstration Projects within the Demonstration Program. The Launch Executive Director is Ted Garrish, former Assistant Secretary for International Affairs at the U.S. Department of Energy.

3.3.2 **Program Sponsors**

Program Sponsors are organizations from the public and private sectors that are supportive and committed to the aims of the DBD Center and willing collaboratively to provide the core funding needed to successfully sustain a multi-year, multi-stakeholder demonstration program. The sponsors fund the organizational infrastructure needed to manage the DBD and the central activity needed to support the Deep Borehole Demonstration Program.

Program Sponsors can come from:

- **The Private Sector** - including Deep Isolation and its global supply chain partners and advisors (which are committed to providing significant resource to underpin the DBD Center) and companies in the nuclear industry wishing to support safe and efficient disposal
- **The Public Sector** – including national Waste Management Organizations and government research institutes
- **The Third Sector** – charities and foundations with an interest in supporting the non-proliferation and environmental protection benefits that can be delivered by deep borehole disposal.

Program Sponsors commit to providing funding and resources, which for most in the first year involves an annual membership fee of $33,000. Deep Isolation is providing significantly higher levels of support through in-kind resources to support the Deep Borehole Demonstration Center Secretariat (see Section 3.3.6 below). In subsequent years, Program Sponsorship fees will be set by the Center's Board of Directors in consultation with existing and potential new Program Sponsors. The expectation is that fees in year two and beyond will be larger, enabling the Center to grow its activities and co-invest in DBD Projects alongside Project Sponsors.

In return for this collaborative core sponsorship of the Deep Borehole Demonstration Center, Program Sponsors secure the following benefits:

- Ability to nominate members of the Center's Board of Directors and Advisory Committee
- Close collaboration with the Center's Board to shape the development of the initial Deep Borehole Demonstration Program
- A seat on the Advisory Committee
- Regular meetings with the DBD Center Board of Directors to steer the program

- Capability building and knowledge transfer for staff (enabled by the potential for staff of Program Sponsor organizations to engage directly with or be seconded into demonstration projects)
- Visibility of forthcoming demonstration projects and any potential procurement requirements for such projects - with an opportunity to recommend potential suppliers from the Program Sponsor's national economy or supply chain
- Access to analysis of outcome and performance data produced by Demonstration Projects.

3.3.3 The Deep Borehole Demonstration Program Plan

The Deep Borehole Demonstration Program Plan is a multi-year, multi-stakeholder program of projects that over time will build up to:

- Deliver an end-to-end (non-radioactive) demonstration of the on-site deep borehole disposal process
- Do this within multiple borehole architectures, including horizontal disposal sections, vertical disposal sections, and various borehole diameters
- Stress-test the process by simulating key 'off-normal' operations, such as recovery of a stuck canister
- Undertake longitudinal analysis, including, for example:
    - Retrieval after multiple years
    - Corrosion analysis
    - Testing the accuracy of predictive models with long-term experimental data.

The initial draft program is described in Section 5. During 2023, the Center will work to refine this with stakeholders and underpin it with:

- A framework of standards that individual DBD Projects must follow
- Plans for evaluating DBD projects, including publication of performance and outcome data
- Plans for disseminating the results of the DBD Program and for ensuring continuous improvement to the Program through stakeholder feedback.

3.3.4 The Deep Borehole Advisory Committee

The Deep Borehole Advisory Committee will be an independent group, meeting biannually or as required to advise the Center on its Program Plan, review progress, and advise on future priorities. Its advice to the Center, along with a summary of how the Center is responding to that advice, will be published in order to assist in transparency and scrutiny of the Center's work.

The Committee will represent key stakeholder interests, with members drawn from three broad communities:

- **Citizens:** representatives of the local community around the Deep Borehole Demonstration site, along with organizations that champion broader citizen interest in radioactive waste management.

- **The scientific community:** individuals with high-level research experience in disciplines relevant to deep borehole disposal, with international recognition for the quality of their work.

- **The international policy and regulatory community:** individuals from bodies that set international or national policy frameworks for radioactive waste disposal, or that have regulatory responsibilities for ensuring the safety of such disposal.

The Chair of the Advisory Committee will be Professor Neil Chapman, a geoscientist with extensive experience of geologic disposal - both in his role as Emeritus Professor in environmental geology, risk assessment and radioactive waste management at the University of Sheffield and as a founding member of both the Arius Association and the ERDO Association. The Center will work with Professor Chapman during 2023 to set up the Advisory Committee, implementing the Terms of Reference at Annex A.

3.3.5 Deep Borehole Demonstration Project Sponsors

The bulk of funds to drive demonstration activities and projects will come from individual or groups of sponsors with specifically aligned interests and project plans, starting with an initial project funded by Deep Isolation and its supply chain partners (see Section 5.6.1 below for more detail on this launch project).

Project Sponsors can be any organization or group of organizations that wish to provide funding for an individual demonstration project conducted at the Center. Such projects must be aligned with the aims of the Center, and they must be conducted pursuant to one or more agreements that set out:

- The funding commitments being made by third parties and/or the Center – commitments that should cover the cost of delivering the project, plus a 10% additional contribution towards the future core costs of the Center
- The scope of the project to be conducted
- The terms and conditions of any oversight conducted by the Center and its advisors – including commitments to:
    - *Follow the documented standards for DBD Center projects*
    - *Participate in DBD Program evaluation, including through publication of all performance and outcome data from the project*
    - *Share detailed performance and outcome data with Program Sponsors in raw granular form.*
- Arrangements for managing intellectual property rights in the project, including the pre-project Intellectual Property rights retained by any participant, the planned use of such pre-project Intellectual Property, and an allocation of rights to any project results and any new Intellectual Property developed in connection with the project.

Section 5.6 below provides details of the two launch projects currently envisioned for Phase 1 of the demonstration.

3.3.6 The DBD Center Secretariat

The DBD Center Secretariat will report to the Executive Director. To minimize costs, the Center Secretariat will be funded initially through in-kind contribution of staff time by Deep Isolation. Its functions will include:

- Providing secretariat services to meetings of the Board of Directors, Advisory Committee and Program Sponsors
- Supporting development and delivery of the DBD Program Plan
- Preparing management accounts and financial statements for the DBD Center.

4 Analysis of technology maturity and prior work

4.1 Overview

In a 2020 meeting of the Reliable Nuclear Fuel Services Working Group of the International Framework for Nuclear Energy Cooperation (IFNEC), presenters concluded [37] 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 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.

This high-level set of requirements represents a good summary of the demonstration requirements for DBD technology, and is covered in full by our Deep Borehole Demonstration Program presented at Section 5 below.

In determining priorities and phasing to move towards this, the Demonstration Program has also been informed by:

- The priorities of stakeholders expressed during the consultation process described at Section 2.3 above
- A review of prior work by government and industry bodies to scope requirements for deep borehole demonstration, as summarized at Section 4.2 below.

4.2 Review of prior work

Prior work performed by Deep Isolation, Sandia National Laboratories, CSIRO and others has advanced the technology to a point of readiness for a demonstration project. The past and ongoing feasibility studies, designs, and performance assessments have defined specific demonstration needs to be addressed by the DBD demonstration project.

4.2.1 Prior work at Deep Isolation

Deep Isolation’s generic (i.e., conceptual) repository designs have been documented in the form of a set of repository functional requirements [38], a COOP [39], and various long-term performance assessments [33], [40], [41]. Recently, Deep Isolation’s long-term performance assessments were expanded to include vertical boreholes [31] and found them to perform similarly well to the horizontal orientation boreholes that form the Deep Isolation primary reference architecture [38]. Optionality between vertical and horizontal allows for an increase in siting flexibility and design optimization approaches. This was discussed extensively in a 2021 feasibility study conducted for the European Repository Development Organization (ERDO) [42], which incorporated the latest economic model assumptions for comparing the costs of horizontal vs. vertical configurations (primarily drilling cost variations) within the same reference geology.

Conceptual design factors and parameters relevant to borehole demonstration

Ideally, a technical demonstration would have conditions as similar as possible to the planned design and implementation of a generic solution. In practice, however, this is difficult to achieve primarily due to cost, but also because the final repository design is site dependent. Thus, the goal is to identify the high priority items that produce technical advancements at the least cost.

Deep Isolation's most detailed repository designs are documented in long-term performance assessments, which must incorporate detailed abstractions of the entire design (including all safety-relevant engineered and geological features). Key repository design parameters derived from these safety analyses for the two architectural variations (i.e., vertical and horizontal) are presented in Table 2.

Table 2. Summary of Deep Isolation's design parameters for horizontal and vertical concepts for PWR spent nuclear fuel assemblies

Parameters	Horizontal [28]	Vertical [31]
Year	2020	2021
Burnup	60 GW-d/MTHM	60 GW-d/MTHM
Waste cooling time*	30 years	30 years
Borehole spacing	100 meters	100 meters
Repository loading density	841 MTHM/km^2	1100 MTHM/km^2
Disposal section max. depth	1- 1.5 km	3 km
Disposal section length/ number of canisters	~1 km 153 canisters	~1.5 km/ 200 canisters
Emplacement zone depth	1- 1.5 km	1.5-3 km
Disposal section borehole diameter	0.48 m	0.48 m
Geothermal gradient	30 °C/km	30 °C/km
Salinity	50,000 ppm (5%) in the under burden	200,000 ppm (20%) below 1 km
Host rock	Shale layer (500 m thick)	>200 m depth: Crystalline bedrock
Host rock permeability	10^{-17} m^2 (horizontal) 10^{-18} m^2 (vertical)	Heterogeneous, depth-dependent fracture-continuum permeability (10^{-20} matrix and ~10^{-17} m^2 overall permeability in the disposal section)
Host porosity	Spatially variable between 5–16%, mean 10%	0.2% (fractures) 1% (matrix)
Host rock thermal conductivity	2 W/m-K	2 W/m-K
Backfill/seal permeability (nominal)*	10^{-16} m^2 ("plug") 10^{-15} m^2 (backfill)	10^{-16} m^2 (seal) 10^{-16} m^2 (backfill)
Backfill/seal permeability (failure scenario)	10^{-13} m^2 , Ref. [33]	10^{-15} m^2
Canister length**	5.5 meters	5.5 meters
Canister spacing	1.0 meters	2.0 meters
Canister lifetime (nominal scenario)***	10,000 years	10,000 years

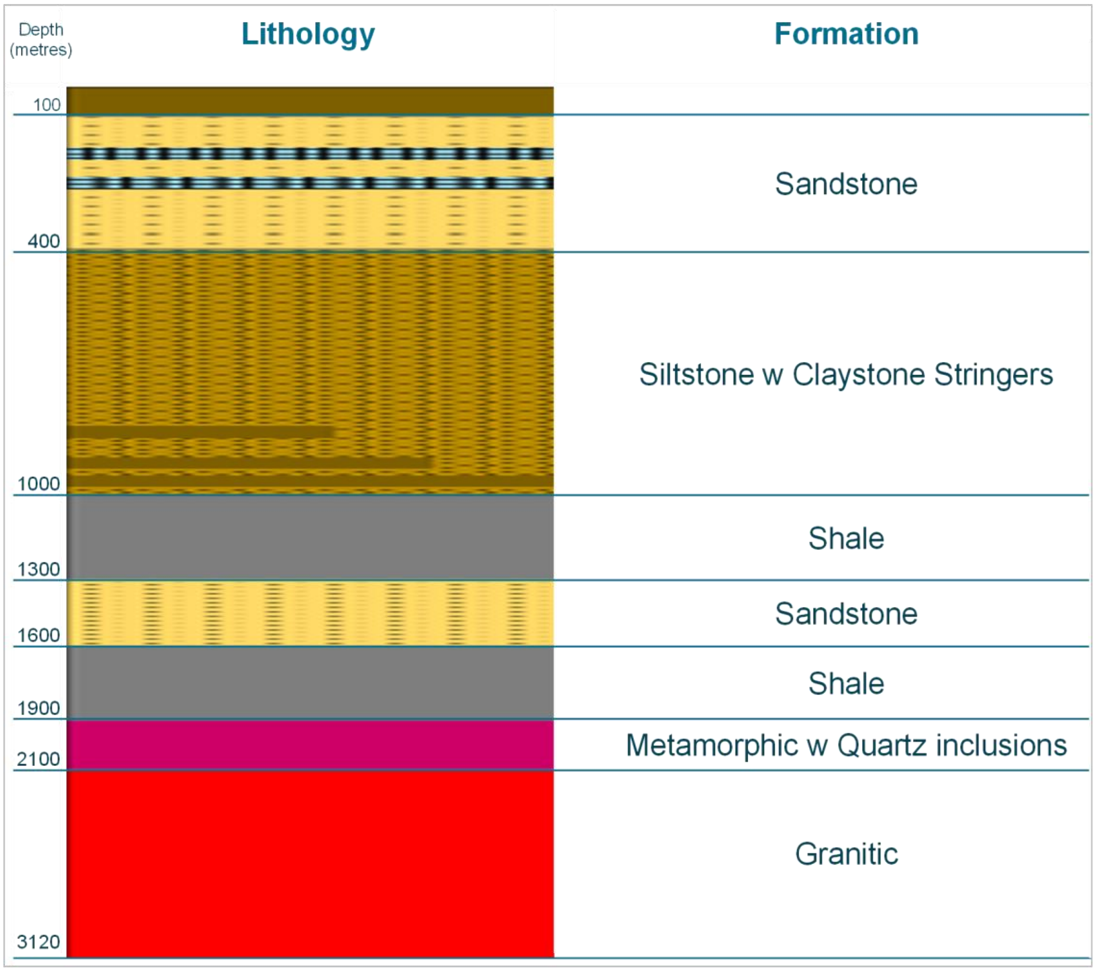
*Ongoing analysis suggests that the minimum cooling time could potentially be reduced to 7 years or less
**Includes endcaps and attachments
**Sensitivity studies in both papers [28], [31] included "early failure" scenarios assuming the canister fails at the onset of repository closure and showing that performance limits were still met with large margins.

In the sensitivity studies on seal and canister performance [33] [31], all cases showed dose increases that were not significant relative to the large (>2 orders of magnitude) safety margin to long-term dose limits, suggesting that their performance (and thus demonstration) requirements may be lower compared to previous geologic disposal facilities.

The conceptual design continues to evolve and mature through a systems engineering process.

Generic borehole designs by Schlumberger
Based on a lithology typical of many European countries and for the purposes of costing studies, Deep Isolation and its partner Schlumberger (SLB) have developed a generic geology suitable for evaluating both vertical and horizontal borehole repositories. This provides a disposal zone in the range of 1.0 – 1.6km sealed within a layer of shale and provides ideal conditions to construct a deeply isolated horizontal repository. Furthermore, it contains deeper layers of granite, of the sort targeted in deep vertical borehole repositories.

Figure 1. Generic geological environment assumed for drilling costing purposes



The high-level specification for these boreholes is given in Table 3.

Table 3. High-level specifications for generic boreholes costed by SLB		
Specification Factors	**Vertical**	**Horizontal**
Length of disposal section	1.5 km	1.5 km
Measured depth (total length of borehole)	3 km	3.5 km
Total vertical depth	3 km	1.5 km
Borehole outside diameter in disposal section	~ 46 cm	~ 46 cm
Borehole outside diameter at surface	~ 122 cm	~ 91 cm
Number of casing sections	3	2

NAC International drillhole canister design

Recently, NAC International completed a report [43] documenting a preliminary design for a "drillhole canister (DHC)" to contain a PWR fuel assembly, supported with an extensive and comprehensive set of analyses covering:

- **Canister mechanical integrity** under accidental drop conditions during handling and within the borehole

- **Canister thermal analysis** during transportation and after emplacement into the borehole
- **Canister criticality analysis** during transportation and after emplacement into the borehole.

A summary of these analyses [44] were published in the proceedings of the Waste Management 2022 conference and ongoing progress on the canister design will be presented at Waste Management 2023 conference[45]. The canister design is further developed than other areas of the borehole design, and a full-scale prototype of the canister is expected to be available for use in the demonstration.

Previous retrieval demonstration

Deep Isolation's first small-scale, small-scope demonstration occurred at the Schlumberger Cameron Training and Testing Facility (CTTF) in Texas. CTTF is a commercial testing, evaluation, and training facility for new geophysical monitoring methods and drilling technologies. This facility is typically used by oil and gas exploration and service companies to test new well equipment and drilling methods and is favorable from a cost perspective because it does not require additional permits or licenses for non-radioactive demonstrations. A small canister with a diameter of 12 cm or 4.5 inches (suitably sized to hold Cs/Sr capsules) was inserted into a horizontal borehole of depth 610 m (2000 ft) and length 122 m (400 ft) and retrieved shortly thereafter.

4.2.2 Prior work of Sandia National Laboratories (2013–2019)

Sandia National Laboratories' (SNL's) prior work on a demonstration borehole plan is extensive and provides a useful starting point and framework for planning Deep Isolation's demonstration. 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 in terms of the importance of the test to borehole performance assessment and its relative maturity [46]. The associated plans [47], [48] and specifications [18] cover the entire set of operations (not just those that are considered novel in terms of deep borehole disposal).

The key demonstration objectives SNL identified were separated into an architecture containing a "characterization" borehole and a "field test borehole." The objectives are summarized below:

- Small diameter 21.6 cm (8 ½'') characterization borehole to full depth.
    - **Construction**: Design drill and construct a small characterization borehole
    - **Test package**: Permit the emplacement of test packages up to 12.7 cm (5'') in diameter [18]
    - **Site characterization**: Collect data needed to characterize the geosphere with acceptable uncertainty and expected hydrogeochemical conditions. A detailed testing plan is given in [48] which includes:
        - Sediments, fluids, and hydrologic conditions
        - Borehole disturbed rock zone
        - Basement rock fluids and hydrologic conditions
            - Borehole stability analysis [48], considering local lithology, stresses, fractures, and pore pressures
        - Coring: Target to recover 5% (by length) of cores (10.2-cm (4-inch) diameter) of the basement rock
- Large diameter field test borehole
    - **Construction:** Design, drill and construct the borehole
    - **Handling:** Mockup canister handling above and below surface. Actual waste package handling operations will make use of shielding, but for the demonstration such shielding may be simulated.

- **In-situ thermal test:** Design of tools or test packages to be used in a borehole thermal test were to be determined [18].
- **Hazards and reliability:** Multiple packaging concepts would be subject to drop testing, and testing of other off-normal (accident) conditions. Multiple test packages will be fabricated to demonstrate repeatable fabrication and testing results, and for destructive testing. The extent of testing, and the number of test packages required, will be determined in the final design.

- Laboratory-based demonstration
  - Engineered materials (i.e., seals [46]) under representative conditions to provide technical basis for evolution of sealing system.

Figure 2 summarizes the borehole characterization tests that were planned for the small-diameter characterization borehole, and Figure 2 summarizes the sequence of operations suggested by SNL [4].

Figure 2. Summary of borehole characterization tests [47]

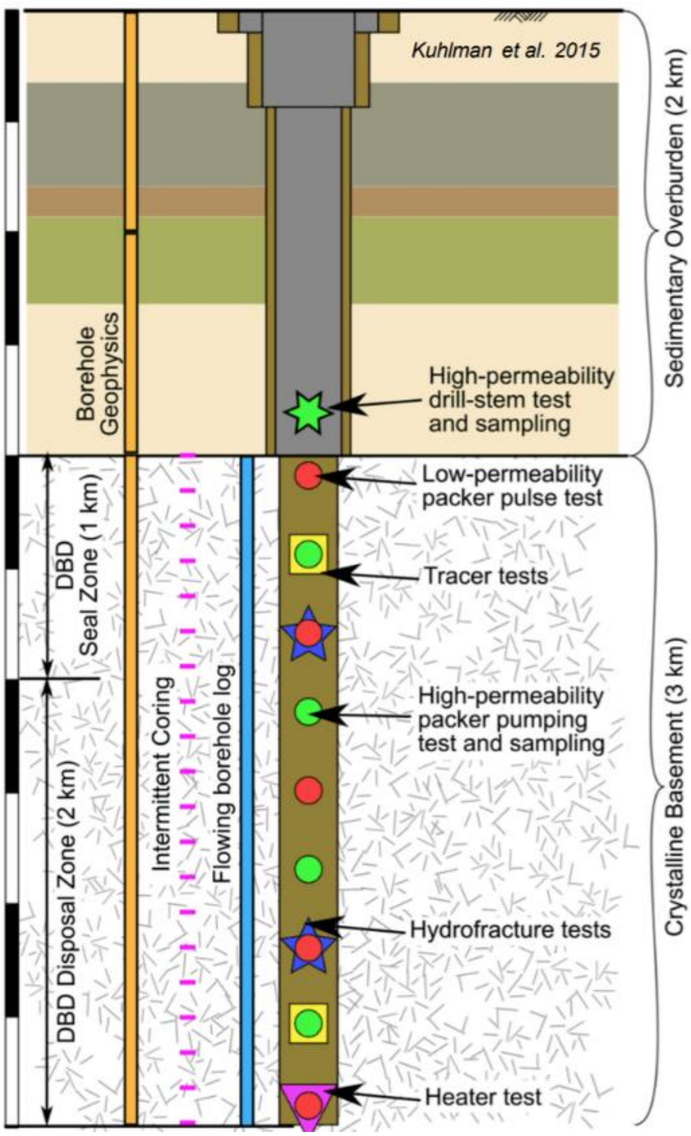
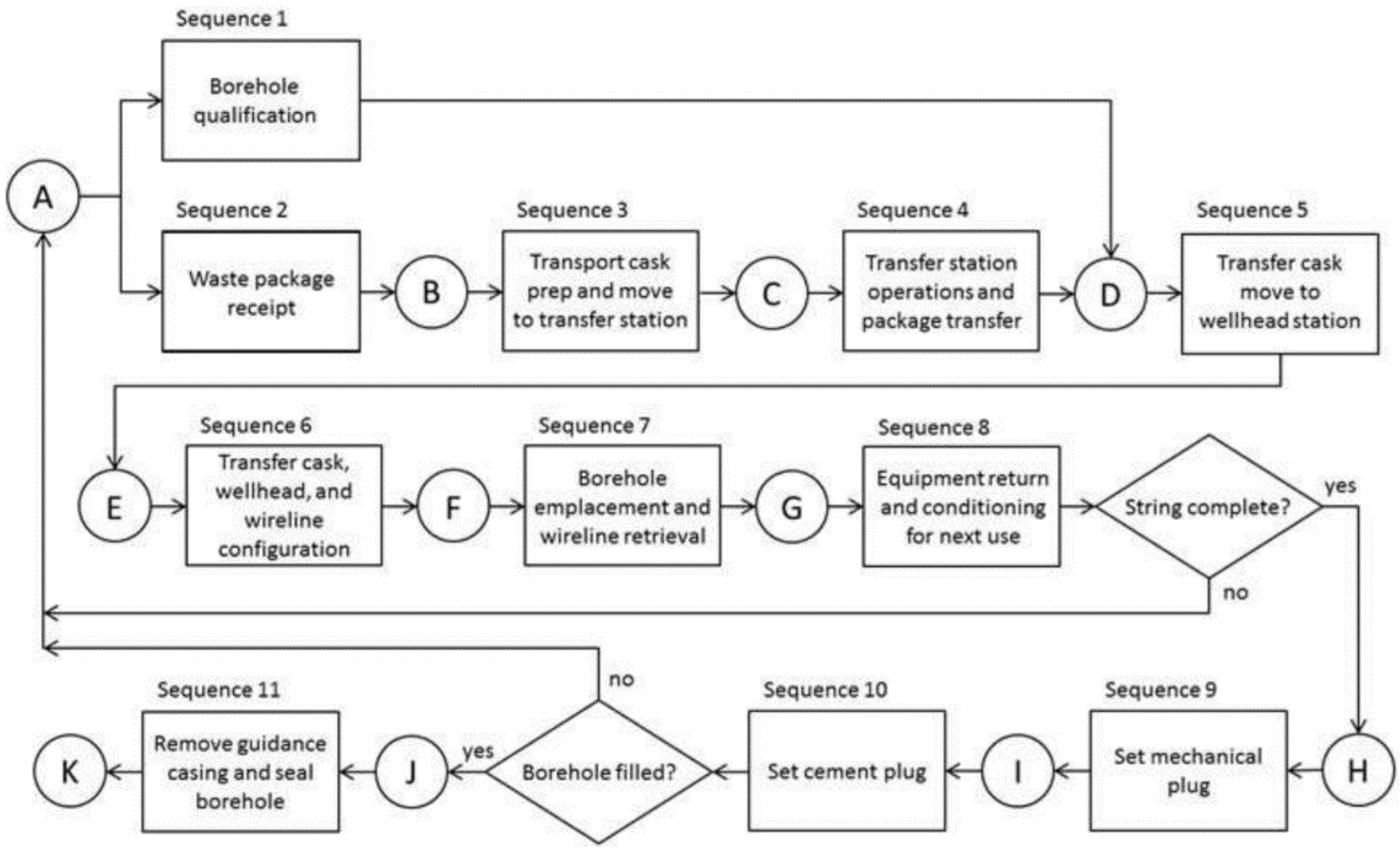


Figure 3. Sequence of operations for transporting, emplacing, and sealing the borehole repository [4]



4.2.3 **CSIRO's demonstration plan and research**

CSIRO, the Australian Nuclear Science and Technology Organization (ANSTO), and SNL are currently collaborating to plan a borehole demonstration [4] with slightly different objectives and scope compared to SNL's previously discussed demonstration program. CSIRO's demonstration design considerations are summarized as follows:

- CSIRO's reference design for a borehole is a 0.7-m diameter, 2000-meter deep demonstration borehole [10], [49].
  - An earlier summary paper makes a call for a demonstration to address the following items:
    - Several iterations of the operational and post-closure safety cases
    - Site characterization
    - Comparative economic analysis between borehole disposal and mined repositories
  - In another paper co-written with SNL [4], it is concluded that a demonstration could be successful even it is not completed at the same depth as the final application. Specifically, a surface handling and emplacement demonstration using surrogate waste canisters in a shallow borehole is deemed sufficient 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 [4].
  - The same paper also suggests that down-hole system characterization techniques should be demonstrated. This could create some restrictions on the type of host rock in which the demonstration occurs, as site characterization techniques will vary depending on the host rock and transport phenomenon.
- CSIRO's current areas of research, demonstration and development include:
  - Geological fault network analysis [10]
    - Conversion of fault trace maps into finite element models for post-closure safety assessment.
  - Borehole mechanical stability modeling [10]
    - Numerically modeling the increase in hydraulic conductivity surrounding the borehole
  - Radionuclide sorption (using molecular dynamics) [10]
    - Developing tools to predict the sorption coefficients in bentonite clay
  - Durable coatings for disposal containers [10]
    - Experimental tests of the performance of various cold spray coatings under chemical and mechanical stresses characteristic of a deep borehole environment.
  - Petrophysical properties and environmental tracers [10]
    - Developing a new vacuum mineral crushing system for the measurement of noble gases and their stable isotope composition (Xe, Ne, He) in fluid inclusions entrapped in mineral grains
  - Performance modeling (including heat and temperature) [10], [19],[46].

4.3 Summary of demonstration needs across organizations

Table 4 compares the specific demonstration needs identified across SNL, CSIRO, and IFNEC.

Table 4. Comparison of needs across organizations that have called for DBD demonstration

Demonstration Needs	CSIRO/SNL (2021) [4]	CSIRO/SNL (2020-2021) [32]	IFNEC (2020) [37]	SNL (2015) [18]
Waste form	Simulated or surrogate (not radioactive waste)			
Site characterization techniques	Include*	Implicitly included (part of a demonstration of the post-closure safety case).	Include	Achieve with a separate, narrower borehole.
Disposal zone/near field characterization		Unclear- not stated how much disposal zone characterization is necessary for safety case.	Include	TBD if heated canister tests were necessary.
Operational safety and emplacement demonstration	Include at full scale but “near surface”*	Full depth of intended application (2000 m) at wide diameter*	Initially at “engineering scale”, but then at full depth and scale.	Full scale and depth of intended application (3-5 km), but simulated shielding can be used.
Retrieval	Include, but not necessarily at full depth. Time frame for retrieval not stated.	Implicitly included (part of a demonstration of the operational safety case).	Include at full depth. Time frame for retrieval not stated.	Include at full scale and depth. Time frame for retrieval not stated.
Sealing and closure		Include*	Include	Include, but specifically only by laboratory testing
Performance monitoring		Include*		
Licensing risk		Achieve positive regulatory feedback on safety cases	Total system performance assessments showing conformity with applicable radiological safety criteria.	
Economic risk		Comparative economic analysis with mined repositories		

*Items are explicitly stated as key elements

4.4 Technology readiness levels

The Deep Borehole Demonstration Program is informed by a formal process of peer-reviewed technology readiness assessment. For each phase of the lifecycle of a DBD repository, Table 5 summarizes the TRL assessment and advancement needs from Deep Isolation’s published technology readiness assessment [51].

Table 5. Summary of TRL assessment [51] and demonstration needs			
Phase	Goal	TRL	Demonstration or Requirement Clarification Needs
Site Characterization	Geological environment	6	Some specific host rock characterization methods will need to be proven at scale and depth for deep boreholes.
	Subsurface processes	6	
Drilling	Drilling	5	Deep horizontal drilling is common, but limited examples where large-diameter boreholes (greater than 12 inches) have been drilled.
	Site characterization of the EDZ	6	
	Site characterization-thermal properties of the host rock	6	
	Borehole stability	4	Affected strongly by retrievability requirements. Cementing of the borehole may also be of higher interest.
Fuel Storage and Processing	Fuel packaging*	6	Effects of fuel aging on difficulty of packaging and handling have not been determined.
Emplacement	Canister emplacement	5	Requires demonstration at full scale with required reliability.
	Axial plugs	4	Axial (bridge) plugs are considered necessary to support retrieval from vertical disposal, but they may not be necessary for the horizontal concept.
	Canister retrieval	5	Retrieval requirements are TBD.
Pre-Closure Monitoring	Natural barriers	6	Monitoring systems for host rock and preferential flow paths have been developed for enhanced geothermal systems (relevant environment). Pre-closure monitoring requirements to support performance confirmation are TBD.
Site Characterization	Geological environment	6	Some specific host rock characterization methods will need to be proven at scale and depth for deep boreholes.
	Subsurface processes	6	

*Not fully addressed with a non-radioactive demonstration TBD: To be determined

Overall, the assessment concludes that spent nuclear fuel handling above ground is the most mature technical process, and that drilling, emplacement, and maintaining borehole stability (as determined by uncertain retrievability requirements) should receive the highest priority in terms of technology development. Other processes such as pre-closure monitoring, canister retrieval, and borehole sealing also may require additional development and demonstration, but the extent will depend on regulatory or engineering requirements that are still being developed.

Many other operations (such as emplacement of fluids into boreholes, site characterization) are considered mature technologies, but there will still be significant benefit in demonstrating these as part of a complete sequence of operations.

5 The Deep Borehole Demonstration Program

5.1 Overview

This section sets out the latest version of the Deep Borehole Demonstration Program, informed by the prior work, technology readiness assessments and stakeholder consultations discussed in previous sections. It describes in turn:

- **The sequence and processes** of DBD operation to be demonstrated in the Program
- **A prioritized and phased approach** for demonstrating the entire sequence and processes of operation through a succession of projects over a number of years
- How the Demonstration Program will inform iterative **development of the Safety Case** for deep borehole disposal
- **Objectives, assumptions and requirements for Phase 1** of the Demonstration Program
- **Scope of Project 1.0 and Project 1.1** – further detail on the two major projects envisioned during Phase 1
- **Quality Assurance processes** to be used across the Demonstration Program.

5.2 Processes and sequence of DBD operation

The Deep Borehole Demonstration Program will address the DBD processes shown in Table 6.

Table 6. Processes of DBD operation to be addressed by the demonstration

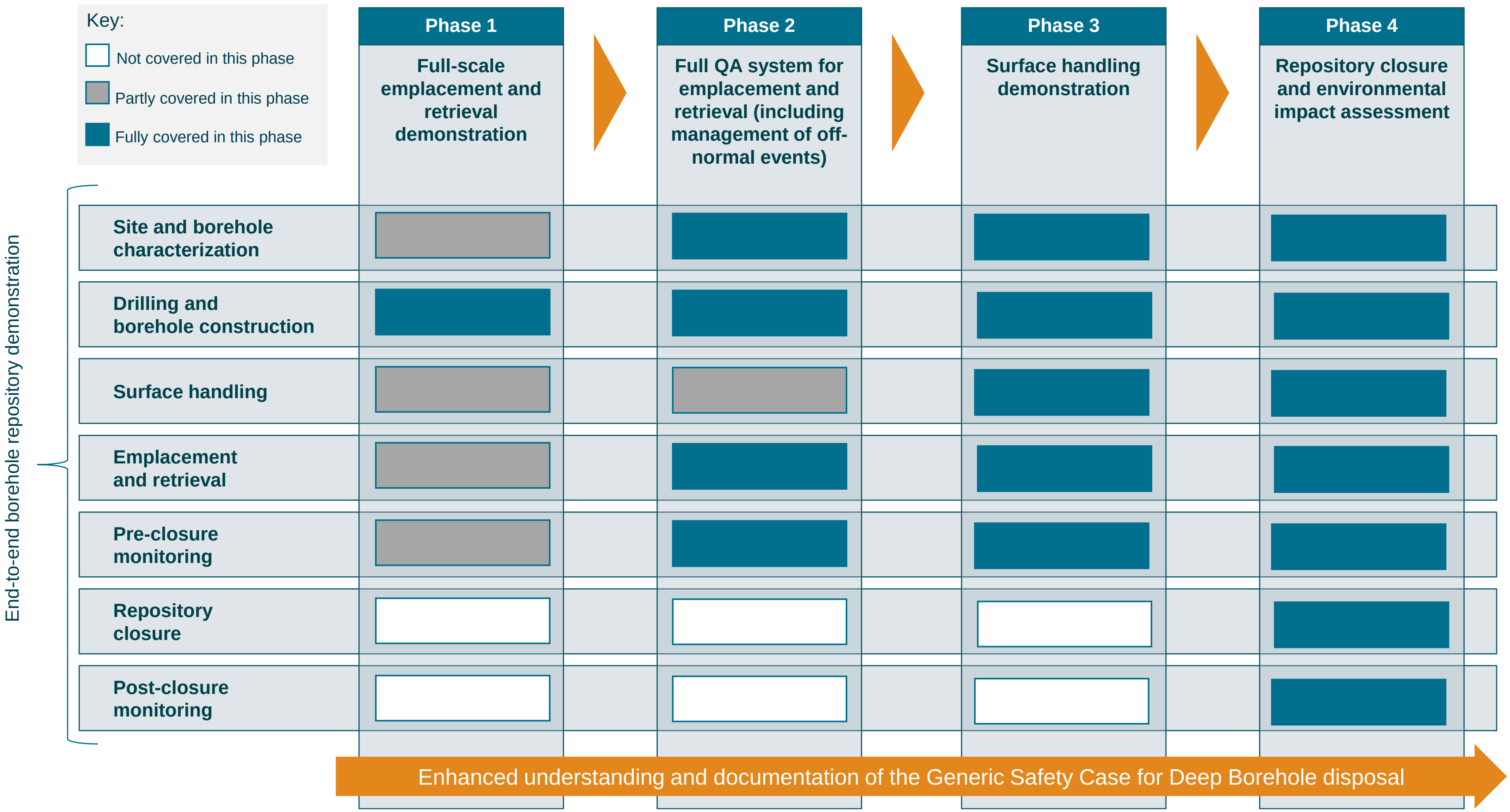
Process #	Name	Description
0	Site and borehole characterization	Drill characterization hole(s), collect data, and develop numerical models to support performance model of a repository.
1	Surface handling demonstration	Demonstrate design basis and accident conditions for handling processes.
2	Drilling	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.

5.3 Phases by priority

The logical sequence of operations shown above does not need to represent the order in which demonstration projects are prioritized and implemented within the Deep Borehole Demonstration Program.

Based on the stakeholder dialogue, prior work and technology readiness assessment discussed earlier, Figure 4 on the following page shows the phasing that the Center currently intends to take forward. This prioritizes **an initial demonstration phase that includes drilling a full-sized hole, emplacing a full-sized waste canister, and retrieving that canister**. This represents a preliminary view that the Center will continue to refine based on the priorities of demonstration participants and available funding.

Figure 4. Proposed phases by priority



The table below breaks down the phases illustrated in Figure 4 above into more detailed activities that are currently under consideration for each phase.

Table 7. A phased approach to delivery of the full demonstration	
PHASE 1	**Full-scale emplacement and retrieval demonstration**
#	**Activity**
1.1	Lift Canister (part of Project 1.0) – lift a full-sized PWR canister as part of a functional requirements test to ensure the canister and lifting adaptors work as expected.
1.2	Drill Full-Sized Hole (Project 1.1) – drill a full-sized PWR borehole to ensure the size can be drilled, cased and readied for emplacement of canisters.
1.3	Borehole Characterization – use oil and gas drilling tools, methods and equipment to characterize the borehole for disposal purposes while it is being drilled. Determine what information can be collected and what other tools, methods and equipment may be needed to complete a full characterization for licensing purposes.
1.4	Emplace Canister – emplace the full-sized PWR canister into the borehole to ensure the canister fits through the horizontal curve and meets the functional requirements.
1.5	Retrieve Canister – retrieve the full-sized PWR canister to ensure it can be retrieved while the borehole is open.
PHASE 2	**Full QA system for emplacement and retrieval – including off-normal events**
#	**Activity**
2.1	Strong Isolation – test the ability to collect samples at depth from the formation without contamination of the sample by drilling fluids or other activities. Send the samples for testing to determine if the sample collection meet the functional requirements.
2.2	Emplace Canister – emplace multiple full-sized PWR canisters into the borehole to demonstrate they can be spaced apart a distance to be specified (e.g. one meter).
2.3	Retrieve Canister – retrieve multiple full-sized PWR canisters to ensure they can be retrieved while the borehole is open.
2.4	Drop Test – drop a full-sized PWR canister to determine if it stops prior to the end of the horizontal curve as modeled.
2.5	Retrieve Stuck Canister – simulate a canister getting stuck in the access hole prior to reaching the disposal section of the borehole. Retrieve the uncooperative stuck canister and document the methods used and lessons learned.
2.6	Pre-Closure Monitoring – deploy monitoring equipment in the demonstration borehole to determine the types of information available while the hole is still open.
2.7	Aquifer Testing – determine tests and monitoring methods to ensure that any potential aquifers are isolated from other formations and particularly the disposal zone.
PHASE 3	**Surface handling demonstration**
#	**Activity**
3.1	Surface Handling – procure the equipment needed to transfer canisters from the receiving area to the disposal rig for emplacement. Mock handling to include the shielding and procedures that would be used for normal operations.
3.2	Heater Tests – determine if heater tests or other testing should be done at this stage.
3.3	Borehole Stability – leave the borehole open for several weeks or months and use tools to determine if the borehole remains sufficient for emplacement and retrieval of the canisters. Consider demonstrating this with further emplacement and retrieval tests.
PHASE 4	**Borehole closure and environmental impact assessment**
#	**Activity**
4.1	Final Testing Determination – determine if any other testing should be performed prior to closure of the borehole.

4.2	Close the Borehole – once testing is complete, seal the borehole with expected processes and materials. Perform testing to determine how the seal performs.
4.3	Post-Closure Monitoring – deploy monitoring equipment that could be used post-closure. This may include smaller, nearby monitoring boreholes.
PHASE N	**Longer-term potential tests**
#	**Activity**
N.1	Long Term Analysis – leave a canister in the disposal section of the well for a number of years and then retrieve to confirm feasibility. Consider corrosion or other aspects for a long-term placement test.
N.2	Repeat the above phases for other borehole architectures such as larger diameter boreholes for vitrified HLW or vertical boreholes. Consider different testing sites for different geologic formations or other site characteristics of interest.

5.4 Generic safety case demonstration objectives

As illustrated at Figure 4 above, an important cross-cutting activity across all phases of the demonstration program will be analysis and deployment of the results to inform development of the generic safety case for deep borehole disposal.

In parallel with physical demonstrations such as drilling and emplacement, maturation of the safety case for deep boreholes (established using computational models) will improve confidence that borehole repositories can be licensed by regulators using existing modelling capabilities and readily obtainable data. Specifically, regulators will review performance models to ensure they are constructed using assumptions and models accurately capturing the relevant and important physics driving radionuclide transport to the biosphere (or at minimum, bound the true transport behavior through the careful selection of conservative assumptions). Proposed approaches to advancing the generic safety case as part of this demonstration are summarized below.

5.4.1 Advancement of post-closure features events and processes (FEPs)

Post-closure FEPs describe the range of important phenomena, initiating events, and boundary conditions accounted within the regulated lifetime of the repository after it is closed. Due to the significantly greater depth and variations in geology achievable with deep boreholes, FEPs included in the safety case will differ from those already studied and documented for mined repositories. Starting in Project 1.0 (see Section 5.6.1 for details), Deep Isolation plans to support the demonstration program by advancing FEPs analysis and the justification FEP inclusions within the generic deep borehole safety case. Current work by Deep Isolation [52] has identified the following FEPs as high priorities for future collaborative work:

- Radionuclide transport through the host rock and overlying geologic units
- Seal and plug degradation
- Radionuclide transport through the disturbed rock zone

5.4.2 Benchmarking of long-term performance models

Benchmarking can take two forms: code-to-code benchmarks [53] and benchmarking against natural analogues [54]. A code-to-code benchmark is accomplished by establishing a common reference case that different investigators separately attempt to model as accurately as possible. Similarity in the results of different investigators builds confidence that the generic safety case is objective (i.e., not dependent on the individuals or methods associated with the model) and that the safety is inherent to the fundamental physics and properties of the repository. On the other hand, variations in the results of different investigators can identify limitations of certain modelling approaches and inform best practices. Natural analogues provide another means to build confidence in the accuracy of performance models. In these exercises, the natural analogue of the repository (i.e., a case where radionuclide transport has taken place with similar phenomena and time scales to a repository) is characterized and the ability of computer models to accurately reproduce the historical behavior of the natural analogue is established.

5.5 Objectives, assumptions and requirements for Phase 1

This section describes the objectives, assumptions and high-level requirements for the initial emplacement and retrieval demonstration in Phase 1.

5.5.1 Objectives

The primary objective of the non-radioactive emplacement and retrieval 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. The Center will provide key results of these demonstration activities to stakeholders, publish results in scientific papers, and invite peer review by others in the demonstration to support verification of the demonstration results.

5.5.2 Assumptions

Execution of the proposed demonstration project will be based on the following assumptions:

- The demonstration project will be carried out at a dedicated demonstration facility.
  - Well drilling permits will be required.
  - The permitting process will factor into the demonstration program schedule
- Engagement of the 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 technical maturity in the Concept of Operations [55] and revisions to the technology readiness assessment.
- Retrievability requirements have not been determined, but potential customers have said retrievability is a key aspect for borehole disposal. Current repository specifications and Deep Isolation's generic Concept of Operations 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 (validation of borehole stability models), so it will be included in the demonstration.

5.5.3 High-Level Requirements

Following are the high-level requirements for the non-radioactive demonstration.

R1. Quantity: The demonstration should include at least one test hole that can accommodate the emplacement of full-sized mock canisters.

R2. Site characterization: The demonstration shall not undertake separate drilling for site characterization purposes, simply drill one borehole intended for use in emplacement. This is because:

- The demonstration is non-radioactive, with commitments to the local community that the resulting borehole will never be used for actual disposal. It is important that the level of site characterization activity is proportionate with that purpose and aligned with local community expectations.

- The technology readiness assessments summarized at Section 4.4 above show that site characterization techniques for the suitability of deep geologic formations are relatively mature (TRL>7)[1].

Accordingly, the site characterization requirement for the Phase 1 emplacement and retrieval demonstration is not to advance scientific understanding or technical maturity but to:

a. **Demonstrate current tools:** That is demonstrate the range and richness of Safety Case-relevant site characterization data that will be delivered simply by the state-of-the-art industry tools that will be deployed during the well planning and well drilling process itself (as summarized at Annex B)

R3. Size: At least one emplacement borehole shall be sized to accommodate mock canisters for spent nuclear fuel from a PWR. This will result in a borehole that is ~46 cm (18.11 inches) in diameter in the disposal zone of the borehole.

R4. Capacity: Between one and three demonstration canisters could be emplaced in the borehole, to be decided (TBD).

R5. Orientation and Depth: Demonstration can be tailored to demonstrate vertical, horizontal or both types of boreholes. Current planning assumptions (to be confirmed through ongoing dialogue with demonstration sponsors as discussed at Section 5.5.4 below) are:

a. **Horizontal total Vertical Depth and Length**: The emplacement borehole would be drilled to a depth of nominally 1.5 km in a formation that is potentially suitable for disposal (e.g., shale, granite, or salt) and would have a horizontal disposal zone of nominally 500 meters where the demonstration canisters would be placed.

b. **Total Vertical Depth**: The borehole would be drilled to a depth of nominally 1.5 km in a formation potentially suitable for disposal (e.g., shale, granite, or salt). The total disposal zone length for a vertical disposal section variant is nominally 0.5 km, but to be decided based on budget constraints.

R6. Mock Canister: One or more of the mock disposal canisters will contain electrically heated elements to simulate the heat generated by nuclear waste. Instruments and sensors will be placed in the borehole in order to gather temperature data and transmit that data to the surface to validate thermal models.

a. The canisters will remain in the emplacement zone of the borehole for a TBD period of time (nominally, weeks) during which time Deep Isolation will study temperature changes in the canisters, the casing, and the role of nearby rock formation in these changes.

b. This data will be used to corroborate the ability of the Deep Isolation performance models to predict the near-term thermal and hydrologic performance of the system.

R7. Emplacement: Emplacement testing could be done at the beginning of the demonstration (away from the heater test). These tests also may include drop tests, runway tests, throughput studies, and evaluation of other aspects.

R8. Retrieval: Retrieval demonstrations will be completed to demonstrate the capability to remove canisters and instrumentation from the access or emplacement zones. Specific retrieval requirements (e.g., duration) are to be decided (TBD).

[1] For example, in the last 4 years, Switzerland drilled 12 site characterization boreholes to depths of ~1.8 km and extensively characterized them to provide input into the ultimate selection of the mined repository location[56]. Over 4,600 core sample 6 km of cores were obtained from these site investigations, and 65 km of geophysical wireline logging data was collected. Thus, extensive site characterization activities would be lower in priority compared to more novel demonstrations related to wide-diameter drilling, surface handling, and canister emplacement and retrieval.

5.6 Scope of projects currently planned for Phase 1

The phasing shown at Section 5.3 and the preliminary requirements for Phase 1 described at Section 5.5.3 above reflect initial dialogue with stakeholders. However, stakeholder views vary on whether the priority for the initial borehole in Phase 1 should be:

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

Against this context, the Center currently envisions two projects during Phase 1.

5.6.1 Project 1.0

This foundational project is sponsored by Deep Isolation. Lasting around nine months, aimed at finalizing the geometry of the initial borehole, and establishing all the technical, industrial and regulatory infrastructure needed to construct and deliver a borehole demonstration. Key components of this foundational project include:

- **Site and Community Engagement** to finalize on-the-ground preparation for the demonstrator and ensure ongoing community consent.
- **Site Characterization:** Development and publication of generic site evaluation criteria for a deep borehole repository and creation of a data-driven Site Descriptive Model for the demonstration site.
- **Canister Manufacture**: Full-scale prototyping of NAC's design for the Deep Isolation waste canister at the Nuclear Advanced Manufacturing Research Centre's state-of-the-art facility in the UK.
- **Engineered Process:** Documenting the Sequence of Operations for deep borehole disposal - the engineered process that will be followed to manage hand-offs and interchanges at each step of the end-to-end process.
- **Operational pre-closure safety case:** Documenting the radiological and non-radiological safety aspects for waste handling that need to be managed when conducting the above Sequence of Operations
- **FEPs Analysis:** Identifying and prioritizing Features, Events and Processes (FEPs) that should be addressed in a detailed safety case for a borehole disposal repository – and that will set the agenda for stress-testing the Sequence of Operations in the new facility.
- **Requirements Analysis for Project 1.1:** Drawing on key inputs from earlier work in Project 1.0 plus consultation with Program Sponsors, potential Project Sponsors and the Advisory Committee, we will finalize plans for the design of the initial borehole drilling and emplacement demonstration for delivery in Project 1.1.
- **Borehole Planning, Design and Permissions** for a full-scale test borehole at the demonstration site that meets the stakeholder requirements specified above, including securing necessary drilling permissions.

5.6.2 Project 1.1:

Building on the foundational work from Project 1.0, this project will demonstrate borehole drilling, borehole stability, canister emplacement and canister retrieval in accordance with the requirements summarized at Section 5.5.3 above. Including through:

- **Drilling and construction of a full-scale test borehole:** Detailed well planning, construction and operation of the borehole at required depths and diameters as established during stakeholder engagement within Project 1.0.
- **Emplacement operations:** Initial demonstration of how the full-scale disposal canister prototype is emplaced and can then, if desired, be retrieved to the surface.
- **Evaluation:** Including measurement, documentation and peer review of demonstration outcomes, and recommendations on how these can be used within the generic safety case for deep borehole disposal.

There may be a pause between Project 1.0 and Project 1.1, dependent on funding availability.

5.7 Quality assurance

For quality assurance, test plans and procedures will be developed as controlled documents and will include:

QA1. Identification of the documents to be developed to control and perform demonstration and tests.

QA2. Criteria for determining the precision and accuracy requirements of test equipment.

QA3. Timing, sequencing, and methods for performing the tests.

QA4. Identification of the item to be tested and the test requirements and acceptance limits contained in applicable design and procurement documents.

QA5. Test prerequisites will include:

(1) personnel qualifications

(2) status of the item and status of other equipment or systems that may affect test performance

(3) suitably controlled environmental conditions

(4) provisions for data acquisition and storage

QA6. Mandatory inspection hold-points for witnessing by the designated organization.

QA7. Provisions for ensuring that test prerequisites have been met.

6 Next steps

The Deep Borehole Demonstration Center welcomes views from stakeholders on the approaches set out in this paper, which it will use to refine and deepen its planning for DBD demonstration.

The Center also welcomes dialogue and engagement from organizations interested in:

- Joining the Center as a Program Sponsor
- Supporting and participating the initial Project 1.0 and Project 1.1 planned for the initial emplacement and retrieval phase of the Demonstration Program
- Undertaking other projects at the Center that support our mission.

Please contact us at info@deepboreholedemo.org.

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ANNEX A: Deep Borehole Demonstration Advisory Committee: Terms of Reference[2]

Purpose of the Advisory Committee

The purpose of the Advisory Committee is to provide independent advice to the Deep Borehole Demonstration Center (“the Center”) on its priorities and plans for undertaking non-radioactive demonstration of systems, processes and technology for disposal of radioactive waste in deep boreholes, in ways that accelerate the global deployment of deep borehole disposal as a licensed system for safe geological disposal of radioactive waste.

Scope of the Committee’s Advisory Function

The scope of the Advisory Committee’s function includes all matters that the Committee deems are necessary in order to meet the above-stated purpose, including but not limited to:

- International developments on research, technologies and markets that impact on the work of the Center.
- Opportunities for greater collaboration with industry, academia and other research bodies, and international partners.
- Supporting peer review of data and findings published by the Center
- Opportunities for dissemination and communication of results of the Center’s work, both by the Center and by the Advisory Committee and its individual members.

Finally – and importantly – the Advisory Committee will publish its formal assessment on the extent to which the Center’s Program Plan is fit for purpose and aligned with stakeholder priorities.

The Chair

The role of the Chair of the DBD Advisory Committee is to:

- Chair the main meetings of the Committee
- Work with Committee members to agree on a work plan for the Committee, including any sub-groups the Committee would like to establish
- Lead the Committee’s process of annual review of the evolving Program Plan for the Center
- Represent the Committee in discussions with other key stakeholders.

The Center will remunerate the Chair for time spent on this work, which is expected to take an average of a day per month or less.

Membership

The DBD Advisory Committee will consist of members, drawn from three broad communities:

- **Citizens:** representatives of the local community around the Deep Borehole Demonstration site, along with organizations that champion broader citizen interest in radioactive waste management
- **The Scientific Community:** individuals with high-level experience of research in disciplines relevant to deep borehole disposal, with international recognition for the quality of their work.
- **The International Policy and Regulatory Community:** individuals from bodies that set international or national policy frameworks for radioactive waste disposal, or that have regulatory responsibilities for ensuring the safety of such disposal.

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[2] The initial template for drafting these came from the Terms of Reference for the UK’s Nuclear Innovation and Research Advisory Board – an independent advisory board established to advise Ministers, Government Departments and Agencies on issues related to nuclear research and innovation in the UK.

Members will be appointed as individuals to provide advice and subject matter expertise independent from the interests of any organization that may employ them, and with no expectation that individuals are representing the views of their employer. Members will be invited to join the Committee for an initial period of two years with membership to be reviewed periodically beyond this point. With the exception of the Chair, appointments will be unfunded, other than the reimbursement of reasonable travel and subsistence costs.

Observers and Supporting Staff

By agreement with the Chair, other participants may be invited to attend meetings as observers to provide support and information.

Meetings

It is anticipated that Committee meetings will take place up to two times per year, with the option to have more or fewer if needed. These meetings may be virtual or in person depending upon need.

Sub-groups

The Committee may convene sub-groups to carry out specific activities as necessary, with participation not limited to Committee members.

Relationship to the Deep Borehole Demonstration Center

The Center is a non-profit corporation established in Texas, USA, operating from in-kind resources of Deep Isolation and contributions from industry, governments and other stakeholders. The Center will:

- Prepare a draft Deep Borehole Demonstration Program Plan for the Advisory Committee to review annually, iteratively enhance that draft in the light of Committee advice, then publish both the final Program Plan and the Committee's assessment of the extent to which it is fit for purpose and aligned with stakeholder priorities
- Provide regular reporting to the Committee on progress against the Program Plan
- Respond to Committee requests for information and analysis on any aspects of the Center's work
- Provide secretariat support for Advisory Committee meetings and any sub-groups that may be convened.

ANNEX B: Site characterization methods and data collection techniques currently planned for demonstration during Phase 1 and 2 of the demonstration program

Current priorities for subsurface data collection in the initial two phases, based on consultations to date, are summarized in the tables below:

- **During Phase 1**, this will focus on demonstration of the site characterization data that can be delivered through the borehole construction process itself: that is, demonstrating the very wide range of Safety Case-relevant data that will be delivered simply by the state-of-the-art industry tools that we will deploy during the well planning and well drilling process itself.

- **During Phase 2**, this will be expanded with a wider set of sub-surface measurement tools and techniques - such as emplacement of a heated and instrumented canister to determine thermal properties and response of the host rock, and longer-term monitoring of wellbore integrity.

It is worth noting that there is no intention to undertake a full site characterization process at the demonstration site. This is for two reasons:

- First, this is intended to be a non-radioactive demonstration – with the resulting borehole never used for actual disposal. It is important that the level of site characterization activity is proportionate with that purpose and aligned with local community expectations.

- The technology readiness assessments summarized at Section 4.4 of this paper show that site characterization techniques for the suitability of deep geologic formations are relatively mature (TRL>7).

This preliminary assessment of the key site characterization techniques to be used and demonstrated will be refined as the site characterization plans and screening criteria are developed.

Phase 1

Site Characterization Method	Description	Importance to Safety
Demonstrate the wide range of site characterization techniques that can be delivered as a standard component of a state-of-the art borehole drilling process, including:	Data acquisition and real-time interpretation during drilling activities. These are 'singular opportunities to acquire data: if data is not collected at the time, it will not be subsequently acquired with the same level of accuracy and precision.	High – an extensive amount of cost-effective geology and engineering data will be delivered as part of the drilling process and is highly safety relevant.
• Drilled cuttings analyses	Rock type Lithological Description Mineralogical and textural characteristics Stratigraphy	Understanding of geological environment to identify dangerous gases, abnormal pressures, and drilling risk

Site Characterization Method	Description	Importance to Safety
• Drilled gas analyses	Gas Identification Gas Ratio Hydrogen (H_2) Hydrogen Sulphide (H_2S)	Understanding of geological environment to identify dangerous gases, abnormal pressures, and drilling risk
• Gas sampling for isotopic analysis	Age dating of fluids	Essential to demonstrate long term isolation of pore fluids in host rocks.
• Cuttings geochemistry	Inorganic chemistry Carbon and Oxygen stable isotopes Elemental analysis	
• Coring	Actual core (with greatest cross-sectional area) across areas of interest	Essential data for understanding rock properties, in-situ fluids and petrophysical calibration of subsequent wireline logs and well tests.
• Lithology log	Strip log of geological and relevant drilling data	
• Composite log	Combination of Lithology log and wireline data for geological interpretation of stratigraphy and geological boundaries	A post-hole section activity used to review precision and accuracy of Lithology Log and build a prognosis of the next hole section. Used in reference to seismic model
• Pore pressure analyses	Real-time pore pressure analyses based on drilled cuttings, gases and drilling data.	Identify abnormal pressures that could lead to a controlled or uncontrolled influx of fluids to wellbore, risk to life, environment, and equipment, including losing the borehole.
• Wellbore stability monitoring	Real-time borehole stability assessment primarily based on cuttings identification and drilling data.	
• Drilling data log (including Corrected d-exponent)	Real-time assessment of potential abnormal pressure in the lithologies being drilled.	
Demonstrate the wide range of site characterization techniques using open-hole wireline logging data acquisition, including the following log/tool types:	These data are acquired using wireline logging tools run on cable from surface. In suitable boreholes some of these same data can be acquired using Logging While Drilling (LWD) tools albeit with greater complexity and cost.	A detailed Data Acquisition Program will be constructed once a Site Descriptive Model has been constructed.
• Electrical Resistivity	Laterlog (formation resistivity measurement with specific conductive muds) Induction Log (measure formation resistivities in boreholes containing oil-based muds and in air-drilled boreholes) Microlaterlog (short / shallow focused resistivity log) Used to identify fluids other than water. Will indicate the relative salinity of a pore fluid.	Understanding the types and disposition of fluids in the subsurface is essential to project the geochemical environment and enable safe and cost-effective drilling operations.
• Nuclear	Gamma Ray Natural Radioactivity Neutron Porosity Induced Gamma Ray Spectrometry Characteristic trends on the gamma ray logs often repeat in logs for wells throughout a given area. These observed characteristics	Used to identify basic petrophysical properties of lithologies including sand to shale ratio, porosity, and permeability. This reduces project risk and uncertainty.

Site Characterization Method	Description	Importance to Safety
	from well to well are used to map the subsurface across the area of interest improving the geological model.	
• Acoustic	The speed at which sound travels through rock depends on its mineral composition and porosity. The relative travel time (velocity) is proportional to a porosity measurement.	Correctly used, will indicate areas of abnormal pressure that could be hazardous to safe drilling operations.
• Dipmeter & Imaging	Can be acoustic imaging (like sonar) or direct visual imaging. The dipmeter shows the dip of the rock and is used to confirm structure or changes in structure. Identification of faults / fractures and their characteristics. Also identifies zones of wellbore instability. The dipmeter is indicative of depositional environment and structure. Also includes caliper logs to assess stress and mechanical impacts on the borehole.	Used to identify zones of wellbore damage, directly investigate the disposition and characteristics of faults and fractures that may reduce wellbore integrity.
• Formation Testing & Sampling	Rock Sampling Fluids Sampling Fluids Pressure Testing Real rock samples are acquired by Sidewall Coring and delivered to surface for analysis. Modular Dynamic Tools (MDT) acquire high quality fluid samples at formation pressure for laboratory analyses with a high degree of accuracy. The MDT tools can also take high density, very accurate rock pressure readings throughout the open hole.	Essential for identifying in-situ pressures, boundary effects and calibrating the relationship between various impacting pressures at depth. Fluid samples acquired will inform pore fluid dating and calibrate geological models for fluid flow demonstrating naturally-occurring radionuclides have historically been trapped in potential host rocks for safety-relevant time periods).
• Seismic	Vertical Seismic Profile (VSP) Prior to running casing, a tool can be lowered in the borehole to acquire detailed seismic data in the region of the borehole to confirm Two-Way-Transit times (TWT) and further calibrate the regional seismic model.	Essential to calibrate regional seismic surveys and extrapolate rock properties away from the wellbores.
Well Testing in Open Hole:		
• Wireline log data and flow-testing	Determine practical rock properties and hydraulic flow.	High importance- rock permeability is an important input for long-term performance assessments. Data is also used to calibrate wireline log data.
• 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. Used to calibrate flow modelling.
• 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, and geochemistry of the deep borehole environment.

Phase 2

Site Characterization Method	Description	Importance to Safety
Waste canister mockup heater test	A heated and instrumented canister is emplaced and used to determine thermal properties and response of the host rock. The canister could remain within the borehole for period of time and data could be collected to support corrosion and retrievability projections.	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 [31], [33]. Significantly reduced cooling periods or certain waste forms may introduce new phenomena (boiling, thermo-mechanical effects) which would increase the importance of this test.
Cased hole wireline logging	Used to identify casing deformation, check cement bond competency, and monitor for corrosion and corrosion products.	Monitoring of wellbore to ensure wellbore integrity which could support projections for retrievability.