Progress towards the Demonstration of Deep Borehole Disposal – 24347

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ABSTRACT

The global consensus is that geological disposal presents the best solution for safe, permanent disposition of spent fuel and high-level waste. But many governments do not yet have clear plans for how to implement a solution. Mined repositories are extremely costly and complex engineering programs, with only a handful of countries such as Finland, Sweden and France getting close to launching their operational facilities. With future energy security concerns and ambitious net zero targets to meet, alternative disposal options must be explored for nuclear to remain a viable energy source for the future. In Europe, this urgency is underlined by the EU Taxonomy regulations introduced on 1 January 2023. These regulations require that – as part of the European Union's net-zero strategy – any investments in new nuclear capacity can take place only if the relevant Member State has a current, detailed plan in place for a facility to dispose of the resulting spent fuel that will be operational by 2050.

Deep borehole disposal (DBD) is an innovative and rapidly maturing technology that represents one of the very few viable options for meeting this timetable.

This paper provides an update on progress towards the end-to-end demonstration of deep borehole disposal for radioactive waste, following the research and studies presented at the Waste Management Symposia in March 2022 and 2023. Informed by those studies, an initial, multinational group of government and industry partners has come together to establish an independent, non-profit organization: the Deep Borehole Demonstration Center. Established on 1 December 2022, this organization was launched publicly at the Waste Management Symposia in February 2023, alongside an initial canister lift test at the Deep Borehole Disposal Center's test facility at Cameron, Texas.

This latest paper on this topic outlines the multi-year, phased program of work that this non-profit, multi-national initiative is looking to deliver. The primary objective of the program is to advance the maturity of the safety case for deep borehole disposal and the technical readiness levels of the disposal concept, including characterization, construction, canister handling, emplacement, and retrieval. The paper reports on progress during 2023 and describes funded projects already in place for 2024 including:

- An award from the UK's Energy Entrepreneurs Fund (EEF) to help Deep Isolation advance the supply chain readiness of its canister design for disposal of Pressurized Water Reactor (PWR) spent fuel and manufacture two canister prototypes for testing at the Deep Borehole Demonstration Center's test facility in Cameron, Texas.
- An award from the U.S. Department of Energy to support laboratory and field testing, also at the Cameron, Texas facility, of the Universal Canister System (UCS). The UCS builds on Deep Isolation's existing PWR canister and will also be able to accommodate advanced nuclear fuels and larger high heat generating waste forms (including existing vitrified waste canisters). The tests will address corrosion phenomena as well as emplacement and retrieval of canisters (after being subjected to subsurface conditions for some period of time).

INTRODUCTION

Since the Experimental Breeder Reactor 1 (EBR-I) 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 [1].

Yet while nuclear power generation has no direct carbon emissions, it creates spent fuel and high-level waste (HLW) that remain hazardous to the environment and human health for thousands of years. There is clear global consensus – across governments, regulators, scientists and the nuclear industry – that the optimal solution for the long-term disposal of this dangerous material is through deep geological disposal [2]. While many countries have yet to decide or publish long-term policies for disposal of high-level nuclear waste, every country that has identified a complete solution has 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, France, Sweden and Switzerland, the total timescale for developing the concept and deploying the solution has been 60-75 years [3].

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 and with a modular approach that is cost-effective even for small inventories [4].

In particular, there is growing international interest in deep borehole disposal and the increasing maturity of the technology and its supporting safety case. Generic long-term performance assessments for horizontal [5] and vertical [6] deep borehole disposal in shale and crystalline rock, respectively – show that both achieve levels of long-term environmental safety that out-perform regulatory requirements by three orders of magnitude, and are robust against degradation of engineered barriers such as seals and highly-disruptive faulting events [7]. This maturing long-term safety case means that stakeholders are increasingly focused on understanding the practical operational aspects of deep borehole disposal.

DESCRIPTION

International Collaboration on Demonstration of DBD: the story so far

Over recent years, there have been increasing calls for a deep borehole demonstration project. An overview of these, published by Deep Isolation in February 2023 [8], summarized the arguments of experts at the International Framework for Nuclear Energy Cooperation (IFNEC) [9], Sandia National Laboratories (SNL), Commonwealth Scientific and Industrial Research Organization (CSIRO) [10], the University of Sheffield [11] in the UK, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) in Germany [12], and the Electric Power Research Institute [13] in the United States.

Research shows that such arguments are widely supported across the international community. A 12-month stakeholder research project by Deep Isolation and the University of Sheffield (of which the results were presented at the Waste Management Symposia in March 2022 [14]), found that regulators, policymakers and waste management practitioners internationally identify that the single most important challenge to be addressed ahead of licensed deep borehole disposal of radioactive waste is a full scale demonstration of the technology. Four out of five research participants would welcome greater international collaboration on DBD, with the highest priority being an end-to-end demonstration of an operational DBD repository.

In the wake of that research, discussions between international stakeholders in radioactive waste resulted in them coming together to establish an independent, collaborative, nonprofit organization: the Deep Borehole Demonstration Center (or “the Center”). The Center was created as a nonprofit organization established in Texas at the end of 2022 and launched publicly in February 2023 [8]. It is funded on an international, public-private-partnership basis and will host progressively advanced DBD experiments and tests, ultimately leading to an end-to-end (non-radioactive) demonstration of DBD technology.

DISCUSSION

Progress of the Deep Borehole Demonstration Center since Launch

On its launch in February 2023, the Center published its Strategic Plan [15], reflecting discussions with stakeholders during its incubation period during 2022. That plan set out a four-phased approach, starting with a full-scale emplacement and retrieval demonstration at the Center’s test facility in Cameron, Texas, then progressing in phases to demonstrate a full Quality Assurance system for emplacement, shielded surface handling, and eventual closure. The latest version of that plan – see Figure 1 below – has been expanded to five phases.

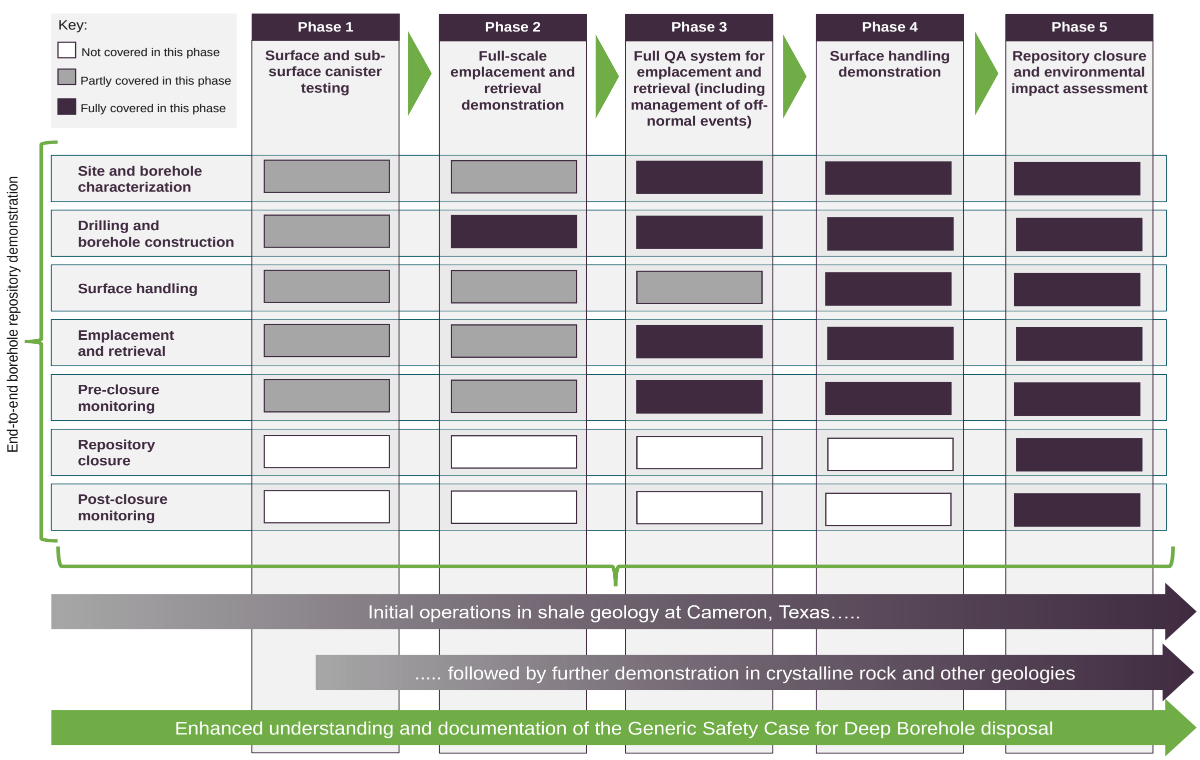

Figure 1. A phased, prioritized program of deep borehole demonstration

The Center has also expanded its Strategic Plan to make clear the Center's intent to demonstrate the technology in multiple geologies, rather than just in the shale geology of its initial test site at Cameron, Texas. Both of these enhancements to the original plan reflect priorities of stakeholders and project funders, and are discussed further in the next sections.

Prioritizing Demonstration of the Disposal Canister

While a full-scale emplacement and retrieval demonstration in a borehole drilled at typical disposal depths and diameters (shown in Phase 2 of Figure 1) remains a priority, it requires significant investment. While fundraising for this effort is in process, the Center's stakeholders have asked the organization to prioritize surface and near-surface testing of the disposal canister as an immediate priority that can be delivered at lower cost, yet achieve rapid and significant benefits for the technical maturity of the overall system. The Center therefore plans to deliver this as a new and additional Phase (shown as Phase 1 of Figure 1).

The rationale for this is rooted in both stakeholder demand and published Technology Readiness Assessments [16]. All published schemes for deep borehole disposal involve use of a disposal canister: an engineered product in which spent fuel assemblies or vitrified HLW canisters can be encapsulated to enable safe and quality-assured operations. Although the canister may not be considered a key safety barrier for long-term performance, it ensures the safe transportation, storage, emplacement, and potential retrieval of the waste. Thus, the canister represents a central component in the delivery of this solution. It is also central in that it represents the pivotal point at which the mature technologies used in DBD (oil and gas technologies used for borehole construction and emplacement, and nuclear waste management technologies used for surface transportation and handling) are designed, engineered and constructed to be physically compatible. Demonstration of the canister's ability to provide this cross-sectoral interoperability is important in raising the Technology Maturity Level of DBD as a total system [16].

The Deep Borehole Demonstration Center has already started on this work – its launch project, in February 2023, involved field testing a mock-up of Deep Isolation's PWR disposal canister. The design, lab-scale testing, and performance of this canister is described in detail in [17], and the experiment at Cameron enabled it to be tested for operational compatibility with standard oil and gas lifting equipment. The test led to some minor design improvements that are now being fed into manufactured prototypes of the canister in conjunction with the UK's Nuclear Advanced Manufacturing Research Centre (NAMRC). These manufactured prototypes will be used for more advanced testing at the Cameron site during 2024 (see Section 'Demonstration Plans for 2024 and beyond' below).

Figure 2. Canister testing and manufacture in 2023

Targeting Multiple Geologies

The Deep Borehole Demonstration Center's initial test program is being conducted in shale geology, at a site in Cameron, Texas where this non-radioactive demonstration program commands strong community support. The Center's stakeholders welcome this, but feedback on the organization's initial Strategic Plan suggests there would also be significant value in undertaking parallel demonstrations in different geologies and jurisdictions.

The updated Program Plan for the Deep Borehole Demonstration Center (as summarized at Figure 1) therefore now emphasizes this multi-site ambition. Progress is already underway, with sites in other countries already having come forward to discuss potential participation in the demonstration program. In May 2023, the Center announced it had signed a memorandum of understanding (MOU) with Norsk Kjernekraft to collaborate on demonstration of deep borehole disposal in crystalline rock in Norway [18]. A further MOU has been signed with TNO, an independent research organization in the Netherlands, with a view to collaborating on a joint demonstration at its Rijswijk Centre for Sustainable Geo-energy. Similar discussions are in place with organizations in other countries, and developing such international partnerships is a priority for the Center over the next year.

Demonstration Plans for 2024 and beyond

The focus of the Deep Borehole Demonstration Center work in 2024 will be three-fold:

- Continuing to grow its membership base and to raise public-private-partnership funding for the long-term, multi-phase, multi-site demonstration program;
- Implementing a significant program of surface and sub-surface demonstration and experimentation on deep borehole disposal canisters; and
- Feeding the learnings from such demonstration into the evolving safety case for deep borehole disposal, including through support to the work of two relevant Coordinated Research Projects (CRPs) being launched by IAEA[A].

Funding is already in place to undertake demonstration with:

- **PWR Canisters:** In February 2023, the UK government's Department for Energy Security and Net Zero announced grant support to help Deep Isolation refine the design of its PWR disposal canister in partnership with the UK's NAMRC [19]. This project aims to: make any refinements needed to tailor the design to UK regulatory requirements and to the spent fuel from the Rolls-Royce small modular reactor (SMR); refine the design to ensure cost-efficiency and carbon-efficiency when manufactured at scale; and deliver two manufactured prototypes of the canister for testing at the Deep Borehole Demonstration Center during 2024/25.
- **The Universal Canister System (UCS):** With support from the US Department of Energy's Optimizing Nuclear Waste and Advanced Reactor Disposal Systems (ONWARDS) program [20], Deep Isolation is leading development of a UCS for the safe storage, transport and disposal of

[A] CRP on "Enhancing Global Knowledge on Deep Borehole Disposal for Nuclear Waste", and CRP on "Challenges, Gaps and Opportunities for Managing Spent Fuel from Small Modular Reactors".

spent nuclear fuel from advanced reactors. Once encapsulated in a UCS canister, the spent fuel from any advanced reactor will be both safe and future-proofed – that is, ready for any option the waste owner may choose in the future: long-term storage, disposal in a mined geologic disposal facility or disposal in a deep borehole repository. As well as handling the light-water spent fuel assemblies targeted by Deep Isolation's standard PWR canister, the UCS will be of wider diameter able to handle advanced nuclear fuels and larger high-heat generating waste forms (including existing vitrified waste canisters). The project is on track to deliver a manufactured prototype by mid-2025.

In support of the commercialization of the UCS, in August 2023, the U.S. Department of Energy announced that – as part of a new $9 million CREATE program ("Creating Revolutionary Energy And Technology Endeavors") – it is awarding a $442k grant for Deep Isolation to test prototype canisters at the Deep Borehole Demonstration Center in Cameron [21].

As illustrated in Figure 3, this project, named Sequential Advancement of Technology (SAVANT) for deep borehole disposal, will consist of:

- A phased experimental program starting with laboratory tests on coupons in representative environments followed by a full diameter and long-term (i.e., months long) emplacement and retrieval test of a canister prototype into an existing borehole at the DBDC. The phases of the SAVANT project are shown in Figure 3.
- Work in partnership with the Electric Power Research Institute to evaluate domestic supply chain options for the UCS in support of commercialization plans for the UCS.

Emplacement will not be at the depths required for waste disposal, but will nevertheless enable:

- A significant expansion of existing corrosion and materials performance modeling of the canister, latching mechanism and casing.
- Testing of standard oil and gas emplacement and retrieval technologies with the prototypic PWR and UCS canister components under representative conditions and time periods.

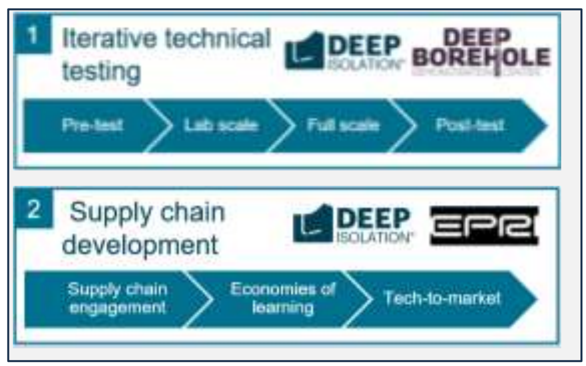

Figure 3. Components of the SAVANT program, as funded by a 2023 ARPA-E CREATE award.

CONCLUSION

There is clear demand for greater international collaboration on deep borehole disposal, and the Deep Borehole Demonstration Center is starting to establish itself as an effective forum that is bringing together different stakeholder interests into a practical program of demonstration. The 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 Deep Borehole Demonstration Center as a Program Sponsor
- Supporting and participating in individual projects within the Demonstration Program
- Undertaking other projects at the Center that support its mission.

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