WHY DEMONSTRATION OF A DEEP BOREHOLE DISPOSAL CONCEPT MATTERS TO THE NUCLEAR INDUSTRY

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Views on the feasibility and utility of deep borehole disposal (DBD) tend to be highly polarized – many skeptics quickly dismiss the concept while proponents avidly promote the benefits. There is room for a more neutral stance to inform the debate. In an effort to find this middle ground, this paper examines DBD from a strategic industry perspective, considering its potential role in the world of used fuel and high-level radioactive waste (HLW) disposal as a potential technology for (1) niche applications and (2) a confidence building option to complement conventional approaches to managing long-lived radioactive wastes. DBD is not a panacea for any and all used fuel and HLW disposal needs, and there are many technical challenges to be overcome for DBD deployment. However, the many challenges are joined by positive attributes that could be realized through a phased DBD demonstration. Given chronic delays of many national repository programs, commercial entities in these countries must continue to manage inventories of used nuclear fuel and HLW without clear disposition paths. In the face of such uncertainty, technology options, like DBD, could offer substantial value to industry. In light of the current lack of alternatives, DBD may warrant further development and demonstration to better define and maximize its potential value.

I. INTRODUCTION

Nuclear utilities in many countries find themselves in a difficult position with respect to the long-term disposition of used fuel – often dubbed "the nuclear waste problem". Nowhere is this more evident than in the United States, where the termination of the Yucca Mountain repository program led to a temporary suspension of NRC licensing actions until NRC updated its regulations to consider the environmental impacts of indefinite continued storage of used nuclear fuel beyond the licensed operating life of reactors [1].[a]

The "nuclear waste problem" is not technical in nature but rather social, political, and economic. A long-standing international scientific consensus has identified a technically sound solution – isolation from the biosphere via deep geologic disposal. To this end, all countries with commercial nuclear power envision a deep geologic repository in their future. Mined repositories excavated at depths less than 1 km and comprising traditional subsurface excavation design and construction represent the universal reference option for implementing geologic disposal.

Several nations, including Finland, Sweden, and France, appear on track to actually construct and operate such mined repositories in the first quarter of this century. However, other countries with prominent commercial nuclear power sectors have seen their geologic disposal programs fail or experience chronic delays. Meanwhile, many more countries with single nuclear units or small fleets, either in service or planned for the future, are challenged by the economy of scale and justification of a major civil project for a relatively small inventory of waste.

Providing diverse options for disposal technology may be a way to reduce uncertainties and mitigate additional delays in some circumstances. In this context deep borehole disposal (DBD) may offer a valuable technology option. Borehole disposal has long been recognized as an alternative since the landmark 1957 U.S. National Academy of Sciences report [2] and was in fact

[a] The June 2012 vacating of the US NRC's 2010 Waste Confidence Decision by the U.S. Court of Appeals required the Commission to revise its generic determination on environmental impacts of continued at reactor storage of used fuel beyond licensed reactor operations and led to suspension of all NRC licensing actions. The revised "Continued Storage of Spent Nuclear Fuel" Rule became effective in October 2014, allowing license actions to resume [1].

used on a limited basis for disposal of liquid radioactive wastes in the United States and Russia. The option has been intermittently evaluated throughout the subsequent six-decade pursuit of a permanent solution for disposal of used fuel and HLW. Borehole disposal was also evaluated as an alternative for fulfilling the U.S. obligation under the 2000 Plutonium Management and Disposition Agreement with Russia to permanently dispose of or denature (via irradiation in a reactor) excess weapons grade plutonium [3].

The Blue Ribbon Commission on America's Nuclear Future, empaneled following the termination of the U.S. Yucca Mountain program, recommended DOE investigate borehole disposal options through the licensed demonstration phase [4]. In parallel, DOE and the U.S. national laboratories have developed and are following a roadmap focused on four activities: (1) site selection for a "*cold*" (*i.e.*, non-radioactive) demonstration borehole; (2) design and drill the borehole; (3) identify and address gaps in scientific understanding; and (4) provide confirmation of feasiblity, capacity, safety and performance to support potential deployment as a HLW disposal option [5,6].

Further development and maintenance of deep borehole technology as a viable disposal option may offer value to national and commercial interests because of the inherent value of expanding the range of options. For activities that rely on successful implementation of a technology for which implementation is dependent on uncertain external drivers, like geologic disposal, options are particularly valuable in mitigating the risk of dead-ends. However, borehole disposal should not be viewed as a miracle cure for nuclear waste management woes. The technical attributes and available scientific evidence associated with DBD may warrant additional nuclear industry interest in the continued development and demonstration of this technology option for managing some forms and quantities of used fuel and HLW.

II. WHO IS THE CUSTOMER?

Mined geologic repositories are big projects with high barriers to entry in terms of costs, timeframes, infrastructure requirements, and institutional involvement. Accordingly, geologic disposal of HLW has traditionally been at the national scale in countries with significant inventories of used fuel and HLW from long-established commercial power and defense programs.[b] However, the smaller physical and economic scale of a single or multiple borehole installation may serve a broader marketplace representing greater diversity of needs, constraints, and drivers. This broader set of customers could include:

- A country without a commercial nuclear power program with a relatively small inventory of irradiated research reactor fuel and/or other orphaned HLW requiring deep geologic disposal to avoid high fixed costs associated with construction of a mined geologic repository.
- A country or utility with a small commercial nuclear power program comprising one or a few units to avoid high fixed costs and the inherent uncertainties of a large scale national program.
- A country or utility looking to start a commercial nuclear power program along with a scalable modular disposal capacity to avoid large up front uncertainties and costs with early deployment.
- A country or commercial vendor seeking scalable modular disposal capacity to disposition HLW from commercial reprocessing of used fuel, including the option for onsite disposal. Use of DBD for problematic minor actinides, such as americium and curium isotopes, could significantly reduce fuel cycle challenges associated with recycling these used fuel constituents in advanced nuclear energy systems and eliminate the need for deploying commercially unattractive transmutation schemes. The ability to tailor physical characteristics of waste forms, especially waste package diameter, could also alleviate the need for larger borehole installations.
- A country or entity seeking disposal of any problematic radioactive waste not eligible for near surface disposal, but compatible with DBD capabilities.

III. DEEP BOREHOLE DISPOSAL CONCEPT IN BRIEF

The benefits and challenges associated with deployment of DBD technology for HLW disposal are well established and competently addressed from many perspectives by others, *e.g.*, Refs. 7-17. For the purpose of this discussion, key attributes and challenges are described briefly to place the DBD concept in context as a potentially valuable alternative for HLW disposal.

III.A. Positive Attributes

The most important attribute of any disposal technology for HLW is its ability to isolate waste from the accessible environment over a sufficiently long timeframe. The definitions of isolation and sufficient timeframe vary by waste characteristics and societal expectations.

The principal selling point for DBD is the potentially high isolation capacity that would inherently come with

[b] The national scale of HLW disposal programs has not meant exclusive implementation by governments. In fact, the two most advanced programs (as of 2014) are led by industry-based consortia – *i.e.*, Posiva in Finland and Svensk Karnbranslehantering AB (SKB) in Sweden.

disposal at depths extending an order of magnitude beyond those envisioned for mined repositories. Disposal of HLW in a suitable crystalline host rock formation at depths below 4 km could offer isolation over geologic timeframes (i.e., millions of years) due to the multiple potential intrinsic benefits of the subsurface environment that accrue with depth. These benefits include[c]:

- Hydrological decoupling: Increasing salinity and density of groundwater with depth that isolates the disposal zone from upper groundwater flows that communicate with the accessible environment (biosphere) and represent the primary vector for contaminant transport away from mined-repositories.
- Long transport path lengths and low water velocities: Physical path lengths and favorable changes in hydrogeological properties of host rock at multi-kilometer depths (low porosities, low permeabilities, and low water contents) result in very low advective rates and very long travel times.
- Chemically reducing conditions that tend to reduce solubility and mobility of many radioelements of concern.

These properties effectively provide multiple natural barriers, reducing reliance on engineered barriers. If confirmed, the elimination of most contaminant transport modes greatly simplies performance assessment to principally understanding the role of the borehole itself, notably the surrounding disturbed zone, the integrity of the casing-grout-rockwall system, and the performance of the systems of borehole seals.

From a security and non-proliferation standpoint, DBD can be appealing due to depth, small footprint and the substantial challenge associated with covert attempts to retrieve fissile inventories. In terms of economics and implementation, the chief attractions of DBD are the small scale and modular nature of deployment. In a manner somewhat analogous to dry versus pool storage of used nuclear fuel, deep borehole disposal for HLW offers the ability to "pay as you go" instead of requiring significant up-front investment for construction of a large facility. While perhaps less compelling for countries with large inventories of used fuel ready for disposal, this modular capacity may prove beneficial for countries or entities with smaller inventories and financial resources, a sentiment expressed by a 2001 U.S. National Academy of Sciences report, which stated: "*…this variation of geological disposal may be suitable for countries with small waste inventories*" [18].

III.B. Technical Challenges and Gaps

As DBD is an undemonstrated technology for HLW disposal, a number of scientific and engineering issues require resolution. Of these, the most important include:

- Adequacy of current understanding of deep hydrogeology and limits on host rock stability with depth for large diameter boreholes;
- Design and demonstration of specialty equipment and instrumentation for drilling, testing, and emplacement operations;
- Manufacturing and supply chain for specialty equipment;
- Directional control and stability for drilling to depth and lack of experience with large diameter boreholes drilled to depths > 4 km; and
- Successful sealing of borehole and demonstration through field testing and performance assessment.

IV. TECHNOLOGICAL MATURITY

A substantial base of expertise, experience, and technology exists on which application of DBD can be built, *e.g.*, Refs. 19-24. Deep drilling technology is mature and in commercial use in related industrial fields where the capacity to access increasing subsurface depths is economically motivated. Not surprisingly, these fall under the energy and mineral industries and include oil and gas extraction, geothermal resource development, and gold and diamond mining. In these applications, drilling to 5 km and beyond is routine, as is drilling of large diameter boreholes (>1 m) to shallower depths in the 0.5 – 1 km range. Table 1 presents a sample of documented mining and drilling experience to illustrate maturity of different critical technology elements relevant to implementation of DBD. What is lacking is experience with these two attributes combined: large diameter boreholes at target depths of 4 – 5 km. While such a demonstration is lacking, there are examples of rapid development and commercialziation of extended drilling capabilities in the face of economic drivers and incentives [13].[d]

[c] Other important characteristics include absence of upward driving forces such as pressurized aquifers and mechanical stability of host rock at depth [14]. These properties may vary by location and would need to be confirmed during the siting process.

[d] Directional drilling made possible by development of downhole drilling technology led to widespread displacement of traditional vertical drilling methods within a three-decade period [13].

TABLE 1. Illustrative Summary of Evidence for Technology Maturity of Key Elements Required for Implementation of Deep Borehole Disposal

Technology Aspect	Evidence	Ref.
Excavation to relevant depths	The eight deepest mines in the worlds, all located in South Africa, have been excavated to depths of 3 to 4 km.	24
Drilling technology	Downhole drilling methods have become dominant within a 3 decade period.	13
	Horizontal drilling runs have exceeded 10 km.	13
Borehole diameter	Geothermal drilling rountinely to 1 – 5 km depths and diameters between 0.215 m (8.5 in) and 0.311 m (12.25 in).	13
	Extensive, routine drilling of >1 m diameter boreholes to 500 m depths for diamond mining, subsurface nuclear weapons testing, and mine shaft installations. Over 500 boreholes were drilled by the United States for weapons testing with diameters of 1.22 – 3.66 m and at depths of 0.15 to 1.5 km. Two in excess of 2 m diameter (3 and 2.28 m) were drilled to depths exceeding 1.5 km (1.7 and 1.9). [Zone A in Table 3]	19, 21-23
Borehole depth	Routine drilling of smaller diameter (to 215 mm) boreholes in 500 m to 5 km range for oil and gas extraction, i.e., 1000's per year.	13
	Routine drilling of small to medium diameter (215 – 311 mm) boreholes of 1 – 5 km depths for geothermal applications.	13
	A small number of scientific boreholes have been successfully drilled to depths in 6 – 12 km range. [Zone C in Table 3]	13
Deep drilling into crystalline rock at depth	2.4 km penetration of a 0.25 m diameter borehole into granite for geothermal application.	13
Integrated demonstration of multiple system elements	Integrated demonstration of deep borehole drilling and casing, with a 0.66 m final diameter borehole drilled to 4 km depth and cased (0.5 m diameter) down to 3.8 km. [Zone B in Table]	20

V. REFERENCE DESIGN AND CAPACITY ESTIMATES

Table 2 summarizes the reference deep borehole design proposed by Sandia National Laboratories for an initial demonstration program in the United States [15].[e] Initial capacities for this reference deep borehole design with a disposal zone between 3 and 5 km below the surface were estimated at 200 – 400 canisters (~ 5 m length). Assuming emplacing of one intact reference 17 x 17 pressurized water reactor (PWR) assembly per canister (~0.43 MTHM[f] per PWR assembly), each borehole could theoretically contain 400 PWR assemblies or 170 MTHM. With fuel rod consolidation [15], this theoretical capacity increases to 250 MTHM of used nuclear fuel. Under this assumption, one borehole could conceivably accommodate used fuel from 10 – 12 years of operation of a 1 GWe unit (assuming 20 MTHM annual used fuel generation), and 4 boreholes could accommodate the used fuel generated in the U.S. annually (assuming 2000 – 2200 MTHM annual generation rate). Other illustrative DBD capabilities for U.S. DOE missions include one borehole to dispose of all cesium and strontium capsules at Hanford, representing a third of total HLW activity under management at the site [6, 25], and three boreholes to disposition 34 metric tons of surplus weapons grade plutonium [26].

[e] Diameters reported are for final borehole segment at depth representing the disposal zone. Deep borehole drilling typically involves a telescoping arrangement of successively smaller diameter boreholes with increasing depth.

[f] MTHM = metric tons of heavy metal

TABLE 2. Reference Borehole Design for U.S. Program (from Arnold et al., 2011 [15])

Total Depth	5 km
Depth of Disposal Zone	2 km
Final (Disposal Zone) Hole Diameter	0.43 m (17.00 in)
Final (Disposal Zone) Clearance (Interior Casing Diameter)	0.34 m (13.38 in)
Reference Canister Length	~ 5 m or less

These approximate figures and bounding estimates are sufficient for illustration purposes. Total waste capacity for a given borehole design will depend on the waste package design and the characteristics of the contained waste, such as fuel rod consolidation.[g]

[g] The U.S. nuclear industry evaluated fuel rod consolidation in the 1980s to increase spent fuel pool capacity. The labor intensive approach was not pursued, as utilities turned to high density pool storage and dry storage [27].

VI. COST

The cost of deploying deep borehole disposal will be one of the key deciding factors for any commercial application. The fact that an integrated demonstration of deep borehole disposal has not been completed means that cost estimates remain highly uncertain. However, the substantial commercial experience with most constitutent subsystem technologies and operations provides a solid basis for preliminary cost estimates for the purposes of demonstration project planning and technology feasibility assessment.

The RD&D effort led by Sandia National Laboratory has considered siting, design and operational aspects of deep borehole disposal for a first-of-a-kind cold demonstration project to resolve important scientific and engineering questions and issues. From this work comes an up-to-date preliminary cost estimate for the demonstration project of $75 million, reflecting siting activities and extensive characterization and testing for a 5 year project timeline [5]. Additional estimates suggest incremental costs of $40 million and a construction schedule under 200 days for each additional borehole installed at a pre-characterized and approved site [15]. The magnitude of these costs, if validated, conceivably place the demonstration of DBD within the reach of entities with constrained budgets such as countries will small nuclear programs or limited HLW inventories.

VII. CROSSCUTTING RD&D INVESTMENT BY GOVERNMENTS AND RELATED INDUSTRIES

Another important factor determining potential advancement of DBDis cross-fertilization by RD&D activities in related industries where economic incentives can accelerate demonstration and deployment of otherwise immature technologies and national programs that may provide funding to support development and demonstration of technologies to address one or more public interest objectives. Since contemporary drilling technology is largely the result of economic drivers, it is likely that further extension of drilling to expand practical application of this technology to HLW disposal will come largely from those same industries, *i.e.*,:

- Fossil fuel exploration, characterization and extraction;
- Geothermal resource development; and
- Mining exploration and shaft construction.

Likewise, government sponsored programs are increasingly looking to synergistic benefits from coordinated, crosscutting RD&D portfolios. The U.S. DOE has signaled its intention to plan on an integrated basis projects to address common subsurface challenges, with funding at levels in the range of $100 millions per year. The products from this expenditure are likely to be of direct benefit to advancing DBD applications as well [28-30]. The relevant domains within the U.S. DOE include:

- Geothermal energy (DOE Office of Energy Efficiency and Renewable Energy)
- Carbon storage (DOE Office of Fossil Energy)
- Subsurface characterization and legacy waste management (DOE Office of Environmental Management)
- Deep Borehole Demonstration (DOE Office of Nuclear Energy)
- Basic geoscience research (DOE Office of Science).

The opportunity exists to leverage resources, experience and expertise across multiple industries and national programs to advance deep borehole disposal as a practical HLW disposal option at various locations around the globe.

VIII. CASE FOR DEMONSTRATION OF DEEP BOREHOLE DISPOSAL

Reviews have concluded that boreholes with diameters on the order of 0.75 m and greater lie outside of the current technology envelope and present challenges too great to be considered practical in the near term [13, 17]. DOE states that disposal of waste packages in excess of 30 cm in diameter are not considered feasible in light of the currently known technology [31].

Demonstration of DBD is supported by the evidence to date (e.g., Table 1) with individual elements of the desired combination of depth and borehole width. Many of the constituent technologies and methods can be considered mature, and important milestones have been reached in terms of depth and diameter (green region in Table 3). Perhaps more importantly, no fundamental technical issues have been identified that would categorically preclude extension of current technology to larger boreholes drilled to 5 km. However, the recent DOE Disposal Options Study [6] scores DBD unfavorably for all waste forms except those suitable for small diameter (<0.3 m or 12 in.) waste packages, implying that additional R&D may be necessary to expand the current technology envelope. The point of a DBD demonstration program would be to address this need and extend the technology envelope into the more desirable regions in Table 3, i.e, Zones B, D, E (yellow region in Table 3), and possibly F (red region in Table 3).

Table 3. Feasibility of Borehole Deployment as a Function of Depth and Diameter (adapted and expanded from Beswick, 2008 [13]).

			Internal Clearance of Bore (Diameter)						
			Small		Medium		Large		Very Large
			< 0.1 m	0.1 m *(4 in)*	0.3 m *(12 in)*	0.5 m *(20 in)*	0.75 m *(30 in)*	1.0 m *(39 in)*	> 1 m
Depth (km)	Shallow	0.5 - 1							**A**
	Medium	2							
		3							
	Deep	4				**B**	**E**		
		5				**D**	**F**		
	Very Deep +	6 - 12		**C**					

Color Legend: **Green = mature application**; **Yellow = feasible application** requiring modest development and involving modest uncertainty; **Red = beyond current technology envelope** requiring substantial development and involving large uncertainty.
Zone A: Diamond mining in Kimberlite deposits [22], underground nuclear weapons testing [19,21], drilling of mine shafts [23].
Zone B: Successful drilling of a 0.66 m diameter borehole cased to 3.8 km depth [20].
Zone C: Three scientific boreholes drilled to depths beyond 5 km range report [13]: 6.7 km, 9 km (0.165 m diameter) and 12.2 km (0.215 m).
Zones D – F represent extensions of current technology via demonstration projects to meet distinct disposal needs in terms of waste package diameter and total disposal inventory.

In spite of an impressive R&D foundation, attention from numerous HLW disposal implementers globally, and relevant experience and technology in allied fields, an actual integrated demonstration of deep borehole concept for HLW disposal has not been completed or attempted [5,12]. Therefore, a field demonstration of the disposal system, especially constructing a cased borehole of appropriate diameter and depth, is needed.

Given the uncertainties involved, an evolutionary approach appears warranted in which the first step would be to meaningfully, but incrementally extend the feasibility range into the innovation region illustrated in Table 3, i.e., zones D, E and F, by developing a sufficient understanding of the hydrological, geomechanical and geochemical conditions that govern the performance of the natural barrier system at depth. In light of renewed interest and available resources, a phased DBD demonstration effort spanning multiple international sponsors with individual interests might involve:

1. Demonstration of medium diameter (~ 0.4 m) DBD for high-level wastes that may fall within current technology constraints, *e.g.*, small-diameter high-activity cesium and strontium capsules at Hanford, USA, or could be tailored to fit within those constraints, e.g., small volumes of problematic, high-activity minor actinides such as americium and curium. [**Table 3, Zone D**]
2. Demonstration of a medium- to large- diameter boreholes drilled to less challenging depth of 4 km for small and assorted inventories of material, *e.g.*, research reactor fuel or small quantities of special nuclear material, present in countries that either do not have commercial nuclear power (and therefore lack a driver for a traditional mined repository program) or desire a nearer term disposal option for appropriate forms and small inventories of other HLW. [**Table 3, Zone E**]
3. Demonstration of a large diameter borehole drilled to 5 km depth for possible disposal of LWR fuel

assemblies and other larger waste forms. [**Table 3, Zone F**]

The proposed U.S. DOE deep borehole demonstration program [5,6] appears capable of achieving Phase 1 objectives and is therefore consistent with this path forward.

IX. CONCLUSIONS

The lack of demonstrated alternatives to mined repositories for permanent disposal of any form or quantity of used nuclear fuel or HLW means that waste owners and generators (typically, governments and facilities such as commercial nuclear power plants) are facing challenges to public confidence and even licensing bases. Because mined repositories are essentially one-of-a-kind projects, demonstration may not be realized until emplacement of waste begins. In this context, value to the nuclear power industry can be realized from tangible evidence of a technically sound alternative, even in interim development phases and even if that technology is not the preferred option. Boreholes with disposal zones lying several kilometers below the surface offer the attractive prospects of a simple safety case relying primary on fundamental intrinsic physical and chemical properties and the performance of a single engineered barrier, i.e, that of the borehole and seals.

While perhaps obvious, it is important to distinguish between support for demonstration of a technology and endorsement of that technology's use. Encouraging the development and maintenance of options does not mean commitment. Conversely, failure to develop and maintain real alternatives strengthens commitment to the status quo which, in the U.S. and several other countries, has been characterized largely by a lack of action.

The ability to potentially deploy DBD at a wide range of sites is a compelling feature that supports greater flexibility for an integrated nuclear fuel cycle, particularly where multiple HLW streams exist that either complicate use of a mined repository or complicate other parts of the fuel cycle, such as handling and recycling of heat generating and neutron emitting curium isotopes. From the point of view of a commercial operator, direct disposal of minor actinides would likely be preferred over managing the added hazards of these constituents in mixed-oxide fuel fabrication and handling.

For DBD, future interest from and relevance to the nuclear industry will depend on the nature of the uncertainties faced. Industry is accustomed to and will tolerate risk associated with innovation, as long as that risk can be bounded by an established technical basis and can be resolved through a reasonable research, development and demonstration program. Unresolved uncertainty in fundamental science, and resulting design constraints, will diminish the relevance of deep borehole disposal as a viable option. Based on historical advancements in mining and drilling technology, evolutionary improvements in deep borehole construction are reasonble objectives that may be worth pursuing in the coming decades.

In light of the potential value of DBD as a technology option for the nuclear industry and the countervailing gaps in understanding of borehole stability and limited experience with large (> 0.5 m) bores at depths exceeding 4 km, programs to expand the technology envelope may be warranted. In the absence of clear show stoppers and contrary evidence, DBD as a modular, scalable, deployable alternative to mined repositories for some forms and quantities of used fuel and HLW has value and merits serious consideration as a technology option.

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