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Short Communication

# Can deep boreholes solve America's nuclear waste problem?

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## HIGHLIGHTS

- To meet obligations, the U.S. should diversify used nuclear fuel disposal options.
- Hydraulic and chemical systems isolated for $\geq 10$ My can be found in deep bedrock.
- Robust concepts in nuclear fuel disposal are enabled by maturing drilling technology.
- Disposal in deep boreholes could ease siting, provide modularity, and lower costs.

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## ABSTRACT

The United States is in need of a new and more adaptive long-term strategy for spent nuclear fuel. In this communication, we outline the fundamental reasons why deep borehole disposal should receive more detailed investigation, alongside traditional shallow mined repositories. This potential solution is supported by advancing drilling technologies and an improving understanding of extremely long fluid residence times in deep bedrock. Radionuclide isolation is supported by verifiable and stable geologic barriers such as long transport distances to aquifers, low permeability, and reducing chemical conditions. The modular nature of implementing deep borehole disposal could offer unique programmatic and economic advantages. Experience with a pilot borehole program will be required to confirm the feasibility of drilling and emplacement operations, and key chemical and hydraulic conditions.

## 1. Introduction

After more than 25 years and a cumulative expenditure of $15 billion (Gaffigan, 2011), the U.S. government's program to dispose of commercial used nuclear fuel (UNF) at the Yucca Mountain site in Nevada has been largely dismantled. UNF containing 66,000 metric tons of heavy metal (MTHM) awaits permanent disposal (Wagner et al., 2012). Litigation arising from the government's failure to meet its contractual obligations to remove UNF from nuclear plant sites beginning in 1998 has already led to more than $2 billion in damage-related payments to utilities, and government liabilities are expected to grow to $20 billion by 2020 (Hamilton et al., 2012). The 1987 Amendment to the Nuclear Waste Policy Act terminated work on alternatives to Yucca Mountain, including all research in crystalline rock. Any new approach will require changes to this legislation. The history of nuclear waste disposal in the U.S. points to the need for a diversified, adaptive strategy capable of accommodating unexpected setbacks as well as technological progress and socio-political priority shifts. Investigating a broader range of disposal options including deep boreholes in crystalline rock will be an important component of such a strategy.

Despite the perceived intractability of nuclear waste disposal, there is a worldwide scientific consensus that safe isolation can be achieved in geologic settings (Heinonen and Raynal, 2003; North et al., 2001). Prior research on UNF disposal as well as maturing implementation plans in Sweden, Finland, Switzerland, and France center on relatively shallow mined repositories at depths up to 500 m in crystalline rock and clay. With a well-established (though not yet operational) basis, efforts to study, site, and construct mined repositories should continue in the U.S. However, advanced drilling technology could allow for disposal at several times this depth, expanding the number of potentially available sites.

Disposal at greater depths ($>1.5$ km) by injecting liquid high-level waste into boreholes was considered by the U.S. in the 1950s (Hess et al., 1957). In the following three decades, deep borehole disposal (DBD) concepts for liquid and vitrified high level waste as well as unreprocessed spent fuel were further analyzed in the U.S. (O'Brien et al., 1979; Woodward Clyde Consultants, 1983). A substantial research program was then initiated by Sweden's SKB during its evaluation of alternatives to mined repositories for

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UNF (Juhlin and Sandstedt, 1989). This program benefited from improved understanding of deep crystalline rock conditions generated by scientific drilling projects including the Kola, KTB, and Gravberg boreholes in Russia, Germany, and Sweden, respectively (SKB, 1993; Smellie and Conterra, 2004). In the 1990s the DOE considered deep boreholes for surplus weapons plutonium disposition (Heiken et al., 1996). This option has also recently been suggested for U.K. plutonium stocks (von Hippel et al., 2012). Separately, DBD was extensively reviewed in the U.K. (Nirex, 2004) and its applicability to various types of UNF and reprocessed high level waste continues to receive attention (Gibb et al., 2012). In the U.S., recent DBD feasibility studies (Brady et al., 2009) benefited from work on enhanced geothermal energy systems using essentially identical drilling technology. With the Yucca Mountain project deemed not workable by the current U.S. Administration, the Blue Ribbon Commission on America's Nuclear Future called for the evaluation of deep boreholes for disposal of UNF (Hamilton et al., 2012).

The fundamental principles of safe geologic disposal include: (1) locating the waste in a deep, stable geology with predictable behavior over the hazardous lifetime of the waste; (2) relying primarily on natural geochemical and hydrological phenomena for containment; and (3) employing a system of multiple, redundant barriers to radionuclide migration, possibly including engineered barriers. In this article, we discuss the potential advantages of deep borehole disposal relative to shallow mined repositories regarding these principles. Although not enough is known at present to fully predict the long-term performance of DBD systems, the goals and scope of a research and development program can be defined. We seek here to stimulate discussion and collaboration among the many institutions and scientific disciplines that must be involved in assessing the feasibility of DBD.

## 2. More geology in disposing of UNF

The principal advantage of drilling deeper into the continental crust (~5 km) is to expand access to stable zones that have demonstrated isolation from flowing groundwater and surface processes (e.g., climate change, erosion) for millions of years. These conditions can be found within cratons, tectonically stable regions of the lithosphere typically composed of Precambrian crystalline basement rocks, covered by younger sedimentary rock of varying thickness (Heiken et al., 1996). Another advantage of deeper emplacement is the orders-of-magnitude decrease in average rock permeability observed in large-scale (time and length) crustal studies (Manning and Ingebritsen, 1999; Stober and Bucher, 2007) (see Fig. 1A).

In the DBD concept, UNF or other waste forms sealed within canisters are stacked in the lower portion of the borehole where preexisting fluid velocities are expected to be smallest and ideally where stratified (i.e., compositionally distinct and segregated) saline groundwater is present. The total vertical length of the emplacement zone depends on two factors: the maximum drilled depth and the thickness of overlying geology required to ensure isolation.

At these depths, the properties of the crystalline basement vary and are not fully understood. Measured permeability at a given site and depth can range over two orders of magnitude (Stober and Bucher, 2007) due to deformation history, nature of extended fracture networks, and the scale at which measurements are made (e.g., packer test vs. borehole injection).

Techniques to assess fluid mobility in deep rock are advancing, as illustrated by the careful study of deep-seated fluids at the KTB VB and HB boreholes (4 and 9.1 km, respectively) (Möller et al., 1997; Smellie and Conterra, 2004). Analysis of crystallized minerals in fractures provides a record of chemistry, flow, and temperature of fluid systems over time. Alkali salt composition indicates whether salinity resulted from extended contact with rocks and the extent and time of mixing with young surface or marine waters. Isotopic analysis can characterize fluid residence and processes at the time scales, depths and conditions typical of DBD. Deep crystalline rocks, which contain uranium at an average concentration of ~1 ppm, provide a well-established natural analog, and have been shown to trap extremely long-lived products of spontaneous uranium fissioning such as $I^{129}$ for tens of million years (Fehn and Snyder, 2005). Similarly isolated pore waters in deep crystalline rock have been documented in North America (Couture and Seitz, 1986; Gascoyne, 2004) These data and methods support a central principle of the geologic disposal strategy: predictions of future performance can only be credible when a strong record of past containment on a time scale exceeding that required for UNF isolation is available and understood.

Once confidence in past geologic isolation has been established, the next task is to demonstrate that the UNF will remain isolated after emplacement and sealing. A key barrier to radionuclide release is the reducing geochemistry prevalent in deep basement waters. A favorable (negative) redox potential is maintained via corrosion of iron (in canisters, liners, etc.) and the subsequent production of hydrogen (Carbol et al., 2012). These conditions limit both the degradation rate of the UNF and the solubility of radionuclides that could be transported by advection or diffusion.

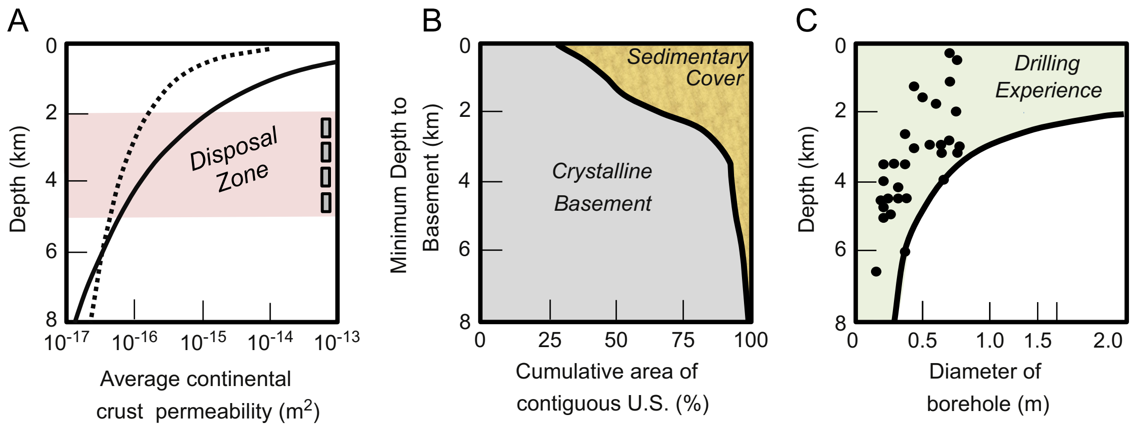

**Fig. 1.** Properties of the borehole disposal concept vs. depth. (A) Semi-log plot of continental crust permeability vs. depth. Solid (-) (Manning and Ingebritsen, 1999), dashed (- -) (Stober and Bucher, 2007). (B) Cumulative area of contiguous U.S. vs. minimum depth to crystalline basement, adapted from Tester et al. (2006). (C) Diameter of boreholes drilled in practice vs. depth, adapted from Beswick (2008).

Selecting locations with a small vertical temperature gradient reduces the temperature (and thus corrosion rate) experienced by the UNF as well as the driving force for fluid motion.

Thermally-enhanced hydraulic transport (to which heat-generating UNF contributes) can also be limited through passive design. For example, a canister containing a single pressurized water reactor (PWR) assembly (as opposed to the 21-assembly canister proposed for Yucca Mountain) achieves the maximum surface area to volume geometry possible with intact PWR UNF, maximizing heat conduction to surrounding rocks. Temperature increases in the fuel are thus minimized. A vertical and slender aspect ratio (in contrast to the horizontally-wide aspect ratio of shallow mined repositories) causes initial heat flow to be primarily radial rather than vertical during the peak temperature period. Thus borehole sealing materials above the emplacement zone remain largely unaffected by UNF heat generation (Pusch and Börgesson, 1992). Lastly, separating boreholes by 200 m or more would minimize thermal interactions between UNF assemblies (Bates et al., 2012). With isolation performance that is likely to be less sensitive to waste characteristics such as thermal output, deep boreholes could support a more streamlined waste acceptance process less constrained by the surface cooling facilities and times required for shallow mined repositories.

The projected safety of some shallow mined repository systems depends extensively on engineered barriers such as canisters and buffer materials (e.g., SKB's current concept for the Forsmark site) (SKB, 2011). Attempts to meet licensing criteria at Yucca Mountain yielded repository designs that progressively diverged from the original goal of safety through geologic isolation. Predicted risk performance became overly dependent on engineered features such as waste packages and drip shields whose behavior over hundreds of thousands of years was difficult to substantiate (Ewing, 1999). To avoid similar complications, DBD studies should continue focusing on naturally-occurring geologic barriers and passive (chemical and thermal) safety features.

## 3. Small modular disposal facilities

In addition to the geological advantages, DBD could also offer programmatic benefits for U.S. nuclear waste management. Crystalline basement rocks reach the surface of roughly 30% of the continental U.S. (see Fig. 1B), so site selection would likely be facilitated by the wide availability of potentially suitable geologies. Site characterization for a deep borehole is likely to cost less than for a candidate mined repository, reducing the financial losses associated with a determination of site unsuitability, on technical or political grounds. Upfront capital investment requirements will also be lessened, since new boreholes can be drilled on demand as additional storage capacity is needed. These factors make DBD compatible with a more decentralized disposal strategy, with regional facilities installed in a phased or adaptive manner, easing transportation burdens (Ewing and von Hippel, 2009) and potentially reducing political risk relative to a single, centralized repository strategy. In a multi-site approach, regulation could be implemented as with nuclear reactors, with separate permitting of sites and generic designs. U.S.-supplied deep borehole technology might also be well suited to small nuclear nations, with attendant economic, safety, and security benefits (Driscoll et al., 2012).

The much greater depth of the boreholes compared with mined repositories puts the emplaced waste at less risk of future human intrusion, either inadvertent or intentional. Thus, continued active safeguarding of the nuclear materials in a deep borehole facility would be less important, and might also be more easily achieved remotely, for example with satellites.

## 4. Feasibility and cost

### 4.1. Technology needs

The maximum diameter and depth of a borehole are constrained by current drilling technology, as demonstrated in Fig. 1C. According to one recent assessment, a finished hole diameter of 50 cm at 4 km is achievable in stable geologies, though not without further development of tools and systems (Beswick, 2008). The KTB-HB borehole was drilled almost 20 years ago with 37.5 cm diameter to 6 km. This approaches the size requirement for intact PWR assemblies (~30.3 cm cross-section diagonal) and provides evidence for the drilling feasibility of DBD. Rock temperatures in the KTB-HB borehole reached 265 °C, exceeding limits on conventional equipment as well as conditions during DBD drilling, which are unlikely to exceed 150 °C. New capabilities were developed in borehole coring and logging, automated pipe handling, online drill-cutting sampling, active and continuous vertical steering, and drilling muds for borehole stability (Emmermann and Lauterjung, 1997). Avoiding severe borehole breakouts and loss of verticality will be vital for DBD canister emplacement, an operation that will require significant testing. As a starting point, the 1986 Nevada Climax tests provide relevant experience in the loading, shielding, and monitoring aspects of UNF (e.g., transferring it out of transportation casks and lowering it into a borehole) although at much shallower depths (Patrick, 1986).

Ongoing fundamental geophysical research in the U.S. is generating additional data and characterization experience using satellite and seismic imaging technologies, and has also involved drilling boreholes up to 3 km in depth in fractured rock (Kerr, 2013). The oil and gas industry continues to make advances in relevant technologies as deeper drilling becomes more standard (Bar-Cohen and Zacny, 2009). New methods such as laser drilling might reduce drilling energy requirements by an order of magnitude (Hecht, 2012). With geometric and cost constraints established by the available drilling technology, DBD is (for now) better suited to highly dense and expensive wastes such as UNF. Other very dilute or large and long-lived nuclear wastes are more appropriately disposed of in shallow mined facilities (e.g., at the Waste Isolation Pilot Plant).

### 4.2. Cost

A 2 km long emplacement zone containing unconsolidated PWR assemblies creates a borehole capacity of ~230 MTHM. The cost of drilling, filling, and sealing a single borehole has been estimated to be $40 million (Arnold et al., 2011), thus the normalized cost is ~$170/kgHM, although this estimate does not include costs associated with transportation, regulatory analyses, and licensing. This is well below the $700/kgHM cost for constructing and loading UNF into Yucca Mountain (DOE, 2008). A total of 475 boreholes (covering ~20 km$^2$) would provide UNF storage capacity equivalent to that of the proposed Yucca Mountain design with expanded capacity (~109,300 MTHM) (DOE, 2008).

If hole diameter is limited by current technology, UNF fuel rod disassembly and consolidation would enable smaller canister diameters, and might also improve loading density and economics. As familiarity at a particular site is gained, drilling and emplacement operations could become standardized (Beswick, 2008). Based on historical drilling projects, per borehole costs would be expected to decrease 20% with each doubling of boreholes drilled at a given site (Brett and Millheim, 1986; McDonald and Schrattenholzer, 2001).

## 5. Conclusion

A clear and growing need exists to establish a more diverse portfolio of technically feasible UNF disposal options in the U.S.

In this communication we present an up-to-date assessment of the programmatic and fundamental geologic isolation benefits that DBD could offer, specifically in the United States. The discussion is made both in the context of recent technology advancements and in light of the historical challenges of achieving broad scientific and political support for mined repositories in the U.S., such as Yucca Mountain.

Careful, consistent comparisons of disposal alternatives would be facilitated by an update of the Environmental Protection Agency's generic performance standard for geologic disposal facilities, 40 CFR 191. Policies clarifying the requirements for future retrievability of UNF would also help to resolve core issues in the design of disposal facilities.

Previous assessments of DBD have raised concerns about the time needed to develop specific drilling and disposal technologies. Recently the DOE announced a target date of 2048 for the opening of a geologic repository (DOE, 2013). On that schedule, ample time will be available for technical development and assessment of both DBD and mined repository options before finalizing disposal plans.

In the near term, the most important step in DBD development, and a pre-requisite for licensing, is to construct a demonstration borehole. Initial goals should include: verifying available drilling capabilities; improving procedures for site selection; and evaluating host medium properties accurately. The extent of drilling-induced changes to the surrounding rock and its permeability should be quantified. Subsequently, down-hole thermal, hydraulic, mechanical, and chemical studies and emplacement tests (using simulated waste canisters) should be carried out. A demonstration borehole project would cost less than 1% of the cumulative expenditure at Yucca Mountain, and within a few years could lay the foundation for the most significant advance in disposal technology in decades.

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