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Deep Borehole Disposal of Nuclear Wastes: Opportunities and Challenges

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The concept of deep borehole disposal (DBD) for high-level nuclear wastes has been around for about 40 years. Now, the Department of Energy (DOE) in the United States (U.S.) is re-examining this concept through recent studies at Sandia National Laboratory and a field test. With DBD, nuclear waste will be emplaced in boreholes at depths of 3 to 5 km in crystalline basement rocks. Thinking is that these settings will provide nearly intact rock and fluid density stratification, which together should act as a robust geologic barrier, requiring only minimal performance from the engineered components. The Nuclear Waste Technical Review Board (NWTRB) has raised concerns that the deep subsurface is more complicated, leading to science, engineering, and safety issues. However, given time and resources, DBD will evolve substantially in the ability to drill deep holes and make measurements there. A leap forward in technology for drilling could lead to other exciting geological applications. Possible innovations might include deep robotic mining, deep energy production, or crustal sequestration of CO_2, and new ideas for nuclear waste disposal. Novel technologies could be explored by Korean geologists through simple proof-of-concept experiments and technology demonstrations.

Keywords: Deep borehole disposal, Nuclear waste, Radioactive, Repository

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1. Introduction

The concept of deep borehole disposal (DBD) involves disposal of high-level nuclear wastes in a borehole drilled deep into the crust. One of the earliest technical studies [1], sponsored by the U.S. Department of Energy (DOE), envisioned narrow diameter boreholes as deep as 11 km, or a 10 m diameter shaft to a depth of 4.3 km. Since then, researchers in, for example, the United States (U.S.), the United Kingdom (U.K.), and Sweden have periodically examined this concept. However, the emphasis remains with mined, geologic repositories rather than DBD.

Researchers in Sweden examined DBD as a potential alternative to a mined repository, as part of their Project on Alternative Systems or PASS Study project [2-5]. In 2006, the NGO Office of Nuclear Waste Review (MKG) reviewed previous research in the context of waste management for Sweden [6]. The study identified advantages of DBD as compared to their mined repository concept (KBS-3). For example, waste emplaced in deep boreholes would reside within a relatively stagnant, density stratified hydrogeologic system, as compared to more active shallower flow systems associated with a mined repository. At placement depths of 3 to 5 km, events, like future glaciation, earthquakes, or human intrusion, would be much less likely to disturb the waste.

In the U.K., two different studies examined DBD [7,8]. The NIREX study pointed out that the safety case for DBD depends fundamentally on containment by a geological barrier system. Under normal conditions, there should be no release of radionuclides through groundwater. This feature makes DBD different from mined geological repositories where safety depends more on defense in depth or multiple barriers. Their review also highlighted several questions for additional study. Also worth noting in the U.K. are contributions by Professor Fergus Gibb at the University of Sheffield, who has researched and published extensively on practical and theoretical aspects of DBD [9,10].

A review provides a useful but now somewhat dated perspective on nuclear power development in countries of East Asia. It also describes opportunities for DBD as a disposal concept [11]. They envision the deep borehole concept as a way to “avoid many of the proliferation-prone steps involved with reprocessing and recycling fissile material from spent fuel”. They also view DBD as potentially more acceptable in social and political contexts and posing fewer risks from the disposal of radioactive materials. In Korea, a review of elements of Sandia’s work represents the most comprehensive efforts on DBD to date [12].

In spite of early interest, work on DBD never progressed beyond the concept stage in either the U.S. or Sweden. They chose a more predictable path with mined geological repositories. Recently, the DOE, through studies at Sandia National Laboratories, has promoted DBD as a novel, technologically advanced option promoted by. DOE has also funded a proof-of-concept study, the Deep Borehole Field Test. However, difficulties in the selection of a candidate site and other issues led to cancellation of this program. This paper reviews the DBD concept, emphasizing ideas developed at Sandia [13,14]. Notwithstanding the renewed activities by the DOE, a recent report of Nuclear Waste Technical Review Board [15] has raised serious concerns relating science, engineering, and safety. Therefore, the review here will address some key questions. For example, what is DBD, what are its most significant advantages and limitations, and whether DBD disposal warrants broader studies in other countries ?

The Sandia concept involves disposal of radioactive waste in boreholes up to 5 km deep, completed in crystalline basement rock (Fig. 1). The waste is contained in a string of containers a depth from 3 to 5 km. Bentonite, concrete, and other materials would seal the upper 3 km of each borehole to isolate the waste from the biosphere. The design would include a lower seal zone, approximately from 2 to 3 km, where the casing is removed to ensure strong coupling of the seal materials to the rocks and to avoid creating pathways from the corrosion of steel casings.

The Sandia design envisions a geologic setting that would assure the isolation of wastes with little long-term performance required from the seals, waste forms and waste packages [13]. NWTRB has issues with this minimalist concept of natural barriers, preferring instead a defense in depth provided by an added system of robust engineered barriers.

There is also some question in the U.S. as to what types waste would be considered for disposal. The emphasis is on DOE-specialty wastes rather than commercial spent fuel [15]. Nevertheless, the Sandia analyses have included PWR assemblies in analyses [16]. With the cancellation of the Deep Borehole Field Test, DOE appears to have reconsidered an approach focusing only on the disposal of their waste independent of commercial spent fuel. Avoiding radionuclide releases during borehole emplacement will require strong containers. If problems develop during loading operations, containers will need sufficient strength to prevent releases. There are two main strategies for loading of containers. Using a string of drilling rods, as many as 40 waste packages could be lowered at one time into the disposal zone. The wireline approach has packages placed individually [17]. Bridge plugs in the casing would prevent a string of containers from crushing those deeper in the hole.

2. The Case for DBD

2.1 Benefits of granite and other crystalline rocks

DBD generally involves crystalline basement rocks at depths > 2 km. Overlying sedimentary rocks are considered as a benefit (Fig. 1) because layers of argillaceous rocks at depth tend be relatively unfractured, usually providing a natural barrier to groundwater flow. Crystalline rocks at shallow depths are already being considered as host rocks for waste disposal in mined repositories, for example, in Sweden and Finland.

The worldwide occurrence of crystalline, basement rocks is advantageous because it provides for useful sharing of experiences with deep boreholes and for future cooperation. The broad distribution of basement rocks in individual countries creates the possibility of distributing the waste among various locations. For example, settings for DBD are distributed across much of the U.S., especially in the stable mid-continent region. Co-locating disposal sites close to the waste generators minimizes the risk associated with the transportation of wastes. It also may offer some potential for expedited licensing, as compared to a single mined repository [18]. Another attractive feature of crystalline rocks is their mechanical strength. Studies with underground laboratories have shown such high-strength rocks are amenable to mining and the creation of stable openings. With deep drilling, the mechanical strength of rocks like granite might resist borehole deformation [19].

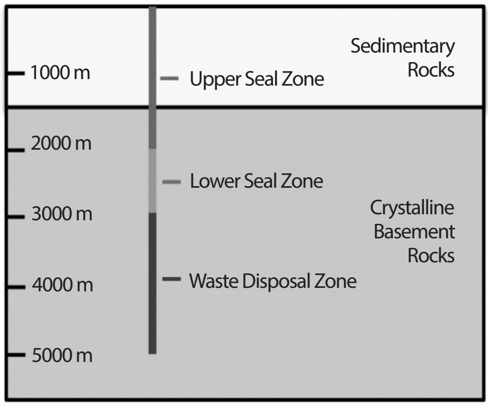

Fig. 1. Sandia National Laboratories' concept for DBD of nuclear waste (modified from [13]).

However, there is relatively limited understanding of the nature of deep crystalline rock systems at depths of 3 to 5 km. The case for crystalline rocks for DBD requires that the rocks actually possess appropriate properties.

2.2 Natural barrier system

The viability and safety of DBD depend primarily on a combination of hydrogeological and geochemical factors that work together to provide natural barriers to radionuclide migration. Key elements include:

i. a long travel time that is promoted by the long distance from where the waste is emplaced to shallow groundwater aquifers, by the inherently low permeability of crystalline bedrock, and generally by absent groundwater flow except for early, time-limited flows driven by thermal expansion of the fluids;
ii. water in the deep subsurface that is particularly saline and stably stratified in a way that counteracts the tendency for buoyant flow due to heating; and
iii. prevalent reducing conditions that minimize the solubility of certain radionuclides and thereby, their overall mass fluxes [15].

One key feature that differentiates deep borehole systems from mined repositories is the much longer travel distance to the biosphere. Assuming relatively slow rates transport of contaminant transport, radioactive decay occurs together with other attenuation processes. The approach to DBD counts on the existence of large areas of relatively uniform crystalline rocks containing near stagnant groundwater conditions, promoted by an absence of continuous fractures and of hydraulic gradients.

Permeability of unfractured crystalline bedrock ranges from 10^{-16} m^2 to 10^{-20} m^2 [19]. Values decline with depth due to increasing confining pressures. For example, measurements on the Westerly granite found a permeability of 350 nd (nanodarcy = 10^{-17} cm^2) at a pressure of 100 bars and 35 nd at 1000 bars (~4 km lithostatic pressure) [20]. Flow typically occurs in nano-sized pores found along the edges of crystals. Crystalline rocks may have much higher permeabilities with a connected network of natural fractures.

If permeabilities are small, then, flow velocities will be exceedingly small even with hydraulic gradients due to topography. Moreover, the presence of high salinity brines (e.g., 150 $g \cdot L^{-1}$, [19]) underlying shallower fresher water represents a case of stable stratification. Thus, in an extensive and largely uniform hydrologic system, there is no inherent reason for flow due to density driving forces.

The physical setting largely precludes natural groundwater flows. Nevertheless, there will be upward transport of radionuclides due to the presence of hot waste and enhanced permeability from drilling damage and leaky seals [19]. Heating will pressurize water in and around the boreholes and create the initial potential for fluid flow. Buoyant thermal convection will maintain flows over longer times [21].

Preliminary results of thermo-hydrologic modeling with a prototype DBD system [21] provide a sense of how a deep borehole system might work. The model represents a cluster of 81 individual disposal boreholes within a 40 km × 40 km area. The 3-D model represents 1,500 m of layered sedimentary rocks overlying 5,500 m of granite. An unstructured grid provides the necessary fine gridding around boreholes. The permeability of granite was assumed to vary from a value of $\sim 3\times10^{-16}$ m^2 at the basement contact (depth 1,500 m) to $\sim 6\times10^{-18}$ m^2 at a depth of 5,000 m. The defects at the boreholes due to annular damage and degraded seals were considered by increasing permeability by a factor of 10 in an area of 1 m^2 at each of the boreholes.

Illustrative results for the central borehole of the cluster found upward flow due to heating and the preferential pathway at the borehole. The maximum vertical groundwater flux declined by orders of magnitude the higher up the flow went, likely showing the effects of horizontal leakoff. In addition, the time at which maximum flux occurred at increasingly shallower depths exhibited large time lags, e.g., ~70,000 years. Elevated temperatures and upward fluxes, however, persisted because of convection. Moreover, with increasing numbers of wells at a particular site, the higher temperatures and upward flows lasted longer.

As mentioned, the safety case relies primarily on geologic barriers. The waste packages will degrade rapidly with seals performing for several thousands of years. The efficacy of the minimalist safety case likely has its roots in earlier modeling [19]. Analyses of simplified, single borehole systems showed temperatures peaking after about a decade and thereafter declining relatively rapidly. Vertical fluxes due to the thermal expansion of water also fell off quickly as heat generated by the waste declined. In their study, buoyancy driven or convective flows were not significant. Therefore, packages and seals need only contribute for a several centuries. However, convection is a more important process than first thought and stable stratification in salinity may not resist long-term convection due to heating.

Other features of basement rocks make them attractive as disposal units. A silicate and alumino-silicate mineralogical composition means that rocks are largely unaffected by heating. The minerals that make up these rocks are poorly soluble in water (e.g., granites are comprised of quartz, feldspar, micas and amphiboles). Thus, there is no prospect for the development of permeability through rock-water interactions.

At depth in crystalline bedrock, groundwater is saline, >> 100 g·L^{-1} with Na, Ca, and Cl as the most common ions. Hot (i.e., > 100℃) and salty water is extremely deleterious to the integrity of steel borehole casings and the simple steel waste packages, envisioned by the Sandia approach. pH values commonly range from 8-9 with estimated Eh values of ~300 mV [l9], placing these waters close to the lower boundary of the water stability field on an Eh-pH diagram. Thus, certain types of waste materials are less soluble under reducing conditions; but this is a topic beyond the scope of this review.

A preliminary assessment of the potential for sorption of radionuclides in the bentonite seals, crystalline basement rocks and overlying sedimentary rocks has been conducted [19]. Significant sorption, indicated approximately by the magnitude of K_D values, reduces advective spreading velocities for contaminants to values much less than the groundwater velocity. The main benefit from reduced rates of contaminant migration is a somewhat longer time for radioactive decay. Preliminary data [19] suggest that the rocks and bentonite seals are capable of sorbing most radionuclides. For a prototypical system, sorption selectivity is - bentonite in seals > sedimentary rocks > basement rocks. ^{129}I and ^{14}C are not sorbed, making them the most mobile constituents.

2.3 Siting criteria and site investigation

DBD purposely targets geologic settings that occur commonly around the world. Key to the safety case then is an ability to identify regions providing superior geologic confinement. Table 1 provides examples of selection criteria. They come from a summary presented in [15], which in turn came from unpublished DOE materials. The next step would involve identifying a smaller candidate sites with the help of site-specific surface from geological, geophysical, and hydrogeological investigations. An obvious prerequisite to these kinds of investigations is the buy-in of local residence and stakeholders.

Table 1. Examples of technical criteria for selecting a potential site for consideration, which would contribute to the safety case (modified from [15] and DOE documents)

Characteristics	Criteria
Depth to crystalline basement	< 2 km
Simple basement structure	No known regional structures, major shear zones, major tectonic features within 50 km
Low seismic and tectonic activity	No Quaternary-age volcanism or faulting within 10 km
Absent flow of fresh groundwater at depth	Absent significant topographic relief to drive deep recharge, old and highly saline groundwater at depth
Low geothermal heat flux preferred	< 75 mW·m^{-2}
Sufficient area for well array	Design dependent
Absent existing contamination	Absent surface or subsurface contamination at proposed site
Minimal disturbances from othersurface or subsurface uses	Prefer sites with minor existing impacts e.g., wastewater injection, oil and gas activities, groundwater production, mining, and potential mineral resources in bedrock

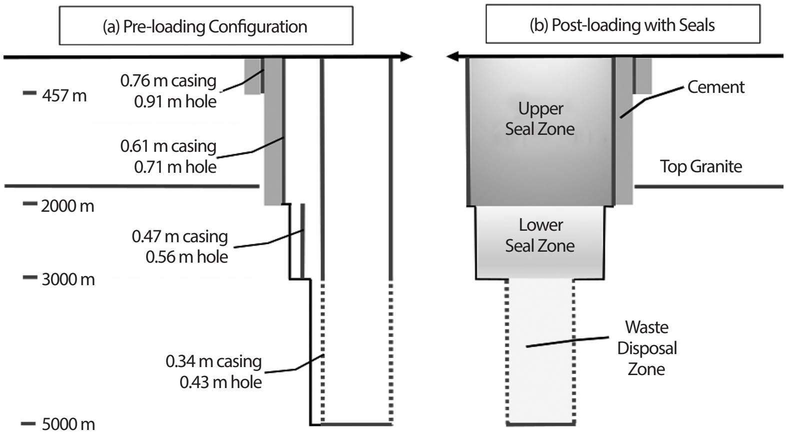

Fig. 2. The Sandia reference design [13] for borehole and casings (red lines) before loading (Panel a) and the overall distribution of seals (Panel b).

2.4 Drilling, casing, and seals

Drilled boreholes in granite have reached depths of 4.5 to 5 km [22-24]. Diameters were typically small, less than necessary for deep waste disposal.

The reference design follows typical oil-drilling practices with multiple casing strings in a borehole with diameters decreasing from 0.91 m, 0.71 m, 0.56 m, and finally to 0.43 m as the borehole extends to 5,000 m [14]. The corresponding casing diameters (OD) are 0.76 m, 0.61 m, 0.47 m, and 0.34 m (Fig. 2a). A continuous 0.34 m casing would guide waste packages from the surface to the bottom of the borehole and facilitate the placement of the waste containers. Through the disposal zone (i.e., lowermost 2000 m), the 0.34 m diameter liner would be perforated to provide for water migration out of the borehole during heating. It would remain permanently in the hole with the containers (Fig. 2b).

With the waste in place, the design calls for removal of the 0.34 m liner through the upper and lower seal zones, followed by most of the 0.47 m casing through the lower seal zone. With both of these casings removed, the seals placed there would be in direct contact with the bedrock wall of the borehole, which reduces the possibility of leakage along the borehole wall (Fig. 2b).

The waste package, envisioned as a 5 m length of standard oil-field casing (340 mm OD and 318 mm ID), could contain CSNF assemblies from either a pressurized water or boiling water reactors [16,19]. A single borehole could contain about 253 metric tons of heavy metal, placed in about 400 containers. However, dismantling used fuel assemblies comes with a significant cost [14]. With DBD, DOE appeared to be considering the possibility of disposal sites dedicated to DOE wastes [15]. However, the cancellation of the Deep Borehole Test appears to signal that DOE is no longer considering this possibility.

Leakage of radionuclides up the sealed borehole and the annular disturbed zone is the most probable way for radionuclides to reach the biosphere. Sandia's reference design [13] involves sealing this potential pathway from the top of the disposal zone to the surface with a series of borehole seals, plugs, and engineered backfill materials. In general, materials used for this purpose provide for small intrinsic permeabilities to minimize advective transport. These seal materials should adhere to the rock wall and fill connected void space in rocks adjacent to the borehole.

Given its inherently low permeability and potential to swell when wetted, bentonite is a desirable sealing material. When wetted, bentonite has a permeability of 10^{-20} m^2, and swells to create pressure on the surrounding rock [13]. Bentonite is also able to sorb many cationic radionuclides because of its large cation exchange capacity and large surface area. With modifications, it can sorb anions, for example: ^{129}I, an important dose driver. Bentonite can inhibit the diffusive transport of anionic radionuclides through anion exclusion [14].

Concrete is already used a seal in oil-field applications. It is an adaptable material and able to accommodate adverse subsurface conditions with adjustments in composition [19]. Typical, permeabilities range from 1×10^{-17} to 2×10^{-21} m^2 over long times [19]. Readers interested in reviewing additional literature on the properties of cement can refer to [13].

The Sandia design envisions a redundant barrier system. It involves dividing the borehole into multiple sections with different kinds of seals. Thus, if an individual seal fails, the potential problem is localized. Specific details concerning the seals, backfills, and plugs above the disposal zone are beyond the scope of this review. Bentonite seals are located towards the bottom of the lower seal zone (Fig. 2b). Cement seals with backfill intervals become more common in the top half of the lower seal zone. The backfill will structurally support the next seal system above it, but its contribution to performance is negligible compared to bentonite and cement. Typical backfill materials would include sand or sand-bentonite mixes [14], and cement, sand and crushed rock. The upper seal zone consists of a series of bridge plugs and longer cement plugs within the casing, following oil-field protocols.

Transformations of seal materials could impair their performance. For example, bentonite may alter to non-swelling clays, such as illite and chlorite. Although cement is a robust material, deterioration can occur due to shrinkage, fracturing, or chemical alteration. Hydrated cement phases alter because they are not uniformly stable under borehole of pressures and temperatures [13].

Importance of the durability of the seal materials has been pointed out by [14]. In essence, seals need to function efficiently through the peak thermal period of < 2000 years. Seals also must be strong enough to resist mechanical loads from overlying materials, potential overpressuring from below, and swelling pressures from bentonite sealing materials. Chemical stability at temperatures of 100 to 200℃ for at least 2,000 years would allow the thermal pulse, the driving force for vertical fluid movement, to pass.

There have been efforts to examine how long concrete seals might last. According to [25] failure is due to leachates like fresh water or brine passing through the seal, causing the calcium-silicate-hydrate matrix to deteriorate. Concrete could last ~200,000 yr assuming a 100 m plug with a permeability ~10^{-16} m^2.

2.5 Field-testing the drilling and measurement technologies

In 2015, DOE set out to begin testing DBD concepts in the field with an actual borehole drilled into crystalline basement. To this end, they released a call for proposals involving the drilling and investigation of a 43.2 cm diameter characterization borehole. The objectives were first to determine whether such a borehole could be drilled to meet specifications, and second to conduct downhole testing to interpret key features of the crystalline rock setting.

Early in 2016, DOE selected a team to begin work at a site in North Dakota. However, DOE subsequently halted and withdrew the project due to inadequate communication and outreach with the local community. Later, in December 2016, they awarded contracts for preparatory work at four potential sites, two in New Mexico, and one each in Texas and Oklahoma. Plans called for one of these four sites to be selected as the location for the deep test hole. In May 2017, DOE decided not to continue with the Deep Borehole Field Test.

There are important lessons with DOE's efforts to field test the DBD concept. First, support from the local community and other stakeholders can be difficult to achieve. Essentially, scientific studies are being viewed as the first step in validating the disposal concept for a specific area. Second and more importantly, their experiences foreshadow the likely difficulty in moving forward in the U.S. with the siting of actual disposal facilities.

3. Issues Bearing on the Efficacy of DBD

A recent report of the U.S. Nuclear Waste Technical Review Board [15] represents the most detailed independent assessment on the feasibility of the deep borehole approach as envisioned by DOE, as well as the Deep Borehole Field Test. The Board challenged fundamental assumptions concerning DBD and pointed out areas of unresolved concern. With the Field Test, the NWTRB was concerned that the study was more about engineering rather than science. Following here is a summary of what appear to be key issues from the NWTRB and other sources [11].

3.1 Is there a logical rationale for DBD?

From reading the NWTRB report [15], one might question whether they ever embraced the rationale for DBD. The concept now appears to encompass only DOE-managed specialty wastes, specifically excluding commercial spent fuel due to concerns about waste size [15]. This focus on DOE-managed wastes effectively diminished the importance of DBD because a mined, geological repository would still be required for the commercial waste. Moreover, that same mined repository could also accommodate the DOE-managed waste.

The Board critically examined the foundational concepts of what proponents of DBD considered to be advantages as compared to a mined geologic repository, for example,

- waste disposal deep in crystalline rocks might provide a simpler and robust safety case,
- deep boreholes have the potential to be sited close to facilities where the waste is generated, minimizing the need for transportation and associated exposure risks, and
- the simplicity of the deep borehole concept and the fact that smaller quantities of waste will be placed at any one site could provide for the earlier disposal of at least some types of existing waste [15].

From a performance point of view, they concluded that neither disposal option had an advantage because the calculated doses for both met prevailing standards for release. They noted further that the deep borehole approach comes with much greater uncertainties because actual sites under consideration in the future may not possess all the favorable attributes thought to be associated with deep crystalline settings. It is likely that suitable sites could be located near DOE facilities now storing waste. With respect to expedited licensing, the Board saw no “compelling evidence” to expect that DBD would “be accomplished more quickly” than a mined repository. Their finding was that DBD would turn out to be complex, not substantially simpler than a mined, geologic repository. Moreover, the licensing process for either approach would follow the same lengthy process.

DBD is considered to be a particularly secure way of disposing of nuclear materials [11]. The deep depth of disposal in a small borehole provides a “formidable physical barrier” to the future retrieval of materials for malevolent purposes. With this disposal scheme, the waste is essentially irretrievable except for perhaps a technically sophisticated and extremely patient group of human intruders.

In the U.S., difficulties in retrieving the waste make the method disadvantageous. Existing regulations for the disposal of nuclear waste in the U.S. require an ability to retrieve the waste for some “reasonable” time period after emplacement [15]. There would likely need to be a compelling reason to abandon the long-standing principle of retrievability.

Therefore, there is the question of why now to continue with DBD? Countries like Sweden considered it and abandoned it in the past. We will take up this topic again in the discussion.

3.2 Technical concerns about the geologic barriers

By most measures, DBD is a decidedly less mature concept for waste disposal, compared to mined, geological repositories. Where this issue shows up is with conceptual models of deep crystalline basement rocks. Around the world, there is a limited number of deep boreholes, most often drilled years ago. It is not surprising then that certain technical concerns with the geologic barrier systems revolve around perceptions of whether current conceptual models are appropriately realistic. Until there are more data and experience available with these deep systems, uncertainties will remain concerning the range in possible behaviors.

The view of the NWTRB is that these deep systems are evidently more complex than is common portrayed and such complexity negatively affects the safety case. The following list provides examples of such complexity:

- the permeability of crystalline rocks at a field scale or larger is likely much higher than the commonly cited range of $10^{-18} \sim 10^{-21}$ m^2 coming from core measurements,
- heterogeneity in permeability due to an intersecting array of faults and fractures would lead to deeper flow, preferential flow, and salinity inversions, and
- post-emplacement disruptions along critically stressed faults could creat permeable pathways, which could develop due to heating and gas generation from microbial corrosion.

There is evidence to indicate why larger-scale permeability values are likely greater than core measurement [15]. The argument is that near hydrostatic pore pressures in fluids at depth will exist in rocks sufficiently permeable to facilitate the redistribution of pore fluids. Within the range of low values mentioned above, hydrostatic pore pressures would not be likely to develop. Heterogeneity in permeability would likely create complicated patterns in flow and geochemistry.

The Board report emphasizes issues related to critically stressed faults. Experience from Oklahoma suggests that small increases in pore pressures in overlying rocks are capable of deep creating earthquakes [26]. There, the pore pressure increase comes from the injection of wastewater from oil-field activities. In the case of DBD, pore pressure increases could come about in two ways. Heating associated with the emplacement of radioactive waste can locally raise pore pressures due to the expansion of water. Another possible cause of increased pore pressure is the production of hydrogen gas from the degradation of waste package and well-casing materials by corrosion or microbial processes.

3.3 Technical concerns about the engineered barriers and emplacement methods

The DOE approach to DBD relies on the geologic barrier provided by deep disposal in low-permeability crystalline rocks. Essentially, waste packages made from oil-field casing material will not contribute to the safety case. The bentonite and cement seals need only perform through the maximum thermal heating period or from about 1000 to 2000 years. However, there are preliminary data to suggest the seals should last longer.

This approach to barriers departs significantly from the historical “defense in depth” strategy, which has guided thinking in the U.S. and other countries for decades. Defense in depth is essentially a concept that leads to the best possible safety case through a combination of engineered and natural barriers [15]. Accordingly, the Board recommended an evaluation of the potential contribution of more robust waste forms and waste packages to the safety case. Such a recommendation anticipates that the natural barrier systems with actual sites may not be as robust as current thinking suggests.

The design of seals is another technical issue of potential concern mentioned by the Board. Clearly, the seals are integral to protecting the dominant pathway by which waste will likely return to the biosphere. Yet, their emplaced properties are largely unknown, as is their efficacy in relation to damage zones in bedrock around the well bore due to drilling.

The disposal system uses a liner to guide waste packages down to the disposal zone. Variants of the procedure involve either drill-stem or wireline emplacement. The potential for problems with this method are obviously greater than those accompanying mined geologic repositories. In the case of an accident, e.g., stuck or dropped containers, a return to normal operations might not be possible. Similarly, radionuclides might leak from a package shortly after emplacement. This collection of potential problems is of such importance that significant efforts here will be required to build the appropriate confidence in the disposal concept.

3.4 Issues in site investigation

Another area of concern is the adequacy of site investigations to support the selection of particular sites. In keeping with the simplified approach and having identified an appropriate region, most of the site-specific investigations would involve down-hole logging, sampling and in situ testing [13]. Given the great depths involved, site characterization would be extremely limited, as compared to a conventional mined repository [15]. However, the geologic isolation afforded deep in crystalline rocks should reduce the burden of site investigation [13]. For example, it might be possible to avoid detailed studies to explore the extent of and pattern of fracturing in the crystalline rock. Such investigations would be necessary with mined repositories, which would likely be located in active, shallow flow systems. Assumptions are that deep flow systems are essentially stagnant without potential to transport radionuclides except during the short period of heating.

Given the rather poor state of understanding of the deep crystalline subsurface, the Board supports a much broader range of testing than envisioned with the Deep Borehole Field Test. For example, testing could also involving surface geophysics, cross-hole tests and more. At this stage, it is not possible to judge whether the proposed expedited site investigations are feasible.

4. Concluding Comments

The concept of DBD for high-level nuclear wastes has developed over several decades. Now, studies at Sandia National Laboratory have examined this concept more seriously. Wastes, emplaced in boreholes at depths of 3 to 5 km, will hopefully remain there, confined by the stable, crystalline rocks, by fluid density stratification, and by absent natural flows. Such a robust natural barrier might require minimal performance from the engineered components of the system. However, an independent review by the NWTRB has raised concerns because the deep subsurface is likely more complicated than expected. The rudimentary scientific understanding of deep crystalline rock settings is in some respects what supports the minimalist approach to disposal. However, experience suggests that the harder one looks at a problem the more complicated it becomes.

The NWTRB has explicitly noted a variety of technical concerns with respect to the geologic barriers, the engineered barriers, the safety of the proposed methods for waste emplacement, and the adequacy of strategies for site investigation. This latest round of criticisms, while different in their specifics, have added to the negative assessments of the past, and implicitly emphasize the inherent benefits of mined, geological repositories as the best technical approach for dealing with spent nuclear fuel.

Worldwide, there has been a huge investment in the mined-repository paradigm for managing nuclear wastes. Technically, these systems provide room to work, a capability to design around geological problems with robust engineered barriers, and more. Largely, the licensing regulations have evolved together with the basic engineering concepts. With so little actual scientific work with DBD in comparison to mined repositories, the “issues” with respect DBD should come as no surprise. In an uneven comparison like this, a dominant paradigm has a tremendous advantage over a new out-of-the-box idea.

With the leadership of geologists around the world, it is likely the concepts of DBD discussed here will have evolved substantially a few decades from now. With continuing support for research, the ability to drill deep holes and make downhole measurements will improve immensely. Thinking back at the early days of mined repositories should remind us that science can progress and difficult problems can end up solved.

Progress in many respects depends upon choices that governments make on where to invest in science. In the U.S., it is, for example, in areas like medicine, satellite technologies, and the unmanned exploration of space. The debate represented here in this paper on DBD illustrates that there is much to learn about the Earth at 5 km. Such geological research is valuable scientifically in its own right. Confirmation comes from an announcement on April 4, 2017 by The Japan News (http://the-japan-news.com/news/article/ 0003619423). A research consortium led by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) will undertake to drill a borehole to the Earth's mantle to a depth of 6 km. Preliminary planning call for a hole at sea in about 5 km of water in the vicinity of Hawaii. The aim of this ambitious long-term study is to learn more about the crust with applications in big science, like plate tectonics and earthquake generation.

There is evident potential with deep boreholes with a variety of exciting opportunities in basic science and technology. A leap forward in technology for drilling could lead to exciting applications. Consider, for example, the possibilities of innovations like deep robotic mining, deep energy production, or crustal sequestration of CO_2. Along the way, such innovation could lead to a better idea for nuclear waste disposal. Such novel technologies for deep drilling could be explored Korean context through simple proof-of-concept experiments and technology demonstrations at somewhat shallower depths. The absence of projects worldwide and the cancellation of the deep drilling test in the U.S. means that with a modest investment, geologists in Korea could grab a significant, leadership role.

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REFERENCES

[1] M.T. O'Brien, L.H. Cohen, T.N. Narasimhan, T.L. Simkin, H.A. Wollenberg, W.F. Brace, S. Green, and H.P. Platt, "The very deep hole concept: Evaluation of an alternative for nuclear waste disposal", Lawrence Berkeley Laboratory, Berkeley, CA, LBL-7089, 47 (1979).

[2] C. Juhlin and H. Sandstedt, "Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential. Part I Geological considerations. Part II Overall facilities plan and cost analysis", SKB Technical Report TR 89-39 (1989).

[3] Svensk Kärnbränslehantering AB (SKB), 1993, "Project on alternative systems study (PASS) final report", SKB Technical Report TR 93-04, SKB Stockholm, Sweden, 14 (1992).

[4] Svensk Kärnbränslehantering AB (SKB), "Systems analysis. Choice of strategy and systems for the management of used nuclear fuel (in Swedish)", SKB Report R-00-32, SKB Stockholm, Sweden (2000a).

[5] Svensk Kärnbränslehantering AB (SKB), "Waste disposal alternative: Very deep boreholes. Contents and scope of the research, development and demonstration (RD&D) programmes required for a comparison with the KBS-3 method (in Swedish)", SKB Report R-00-28, SKB Stockholm, Sweden (2000b).

[6] K.I. Ahall, "Final deposition of high-level nuclear waste in very deep boreholes: an evaluation based on recent research of bedrock conditions at great depths", MKG Report 1, Swedish NGO Office of Nuclear Waste Review (MKG) (2006).

[7] NIREX, Inc., "A review of the deep borehole disposal concept for radioactive Waste", NIREX Report No. N/108, 78 (2004).

[8] J. Beswick, "Status of technology for deep borehole disposal", prepared for the UK Nuclear Decommissioning Authority (2007).

[9] F.G.F. Gibb, "High-temperature, very deep, geological disposal: a safer alternative for high-level radioactive

waste ?", Waste Management, 19, 207-211 (1999).

[10] N. Chapman and F.G.F. Gibb, "A truly final waste management solution – Is very deep borehole disposal a realistic option for HLW or fissile material ?", Radwaste Solutions, July/August, 26-35 (2003).

[11] D. von Hippel and P. Hayes, "DBD of Nuclear Fuel and High Level Waste as a Focus of Regional East Asia Fuel Cycle Cooperation", Austral Special Report 10-03A, 15 December, 47 (2010).

[12] S. Yun and C.L. Kim, "Deep borehole concept of spent fuel for implementation in Korea", J. Nucl. Fuel Cycle Waste Technol., 11(4), 303-309 (2013).

[13] B.W. Arnold, P.V. Brady, S.J. Bauer, C. Herrick, S. Pye, and J. Finger, "Reference design and operations for deep borehole disposal of high-level radioactive waste", SAND2011-6749, Sandia National Laboratories, Albuquerque, 64 (2011).

[14] P. Brady, B. Arnold, S. Altman, and P. Vaughn, "Deep borehole disposal of nuclear waste: final report", SAND2012-7789, Sandia National Laboratories, Albuquerque, 30 (2012).

[15] U.S. Nuclear Waste Technical Review Board (NWTRB), "Technical evaluation of the U.S. Department of Energy deep borehole disposal research and development program", A Report to the U.S. Congress and the Secretary of Energy, 32 + Appendices (2016).

[16] G.A. Freeze, B.W. Arnold, P.V. Brady, D.C. Sassani, K.L. Kuhlman, R. MacKinnon, and E. Hardin, "Siting guidelines for a deep borehole disposal facility", International High-Level Radioactive Waste Management Conference, Charleston, South Carolina, April 12–16, 618-623 (2015).

[17] J.R. Cochran and E.L. Hardin, "Handling and emplacement options for deep borehole disposal conceptual design", Revision 9. SAND2015-6218, Sandia National Laboratories, Albuquerque, 30 (2015).

[18] Sandia National Laboratories (SNL), "Project Plan: Deep Borehole Field Test", SAND2014-18559R. Rev. 0. September, Sandia National Laboratories, Albuquerque (2014).

[19] P.V. Brady, B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein, "Deep borehole disposal of high-Level radioactive waste", SAND2009-4401, Sandia National Laboratories, Albuquerque, 74 (2009).

[20] W.F. Brace, B. Walsh, and W.T. Frangos, "Permeability of granite under high pressure", J. Geophys. Res., 73(6), 2225-2236 (1968).

[21] B.W. Arnold and T. Hadgu, "Thermal-hydrologic modeling of deep borehole disposal system", High-Level Radioactive Waste Management Conference, April 30, SAND2013-3179C, Sandia National Laboratories, Albuquerque (2013).

[22] J. Baumgartner, T. Gandy, G.T. Hettkamp, and D. Tez, "Drilling of hot and fractured granite at Soultz-sous-Forêts", ENGINE Mid-Term Conference, January 9-12, GFZ, Potsdam (2007).

[23] G. Beardsmore, "The burgeoning Australian geothermal energy industry", Geo-Heat Centre Quarterly Bulletin, 28, Oregon Institute of Technology, Klamath Falls, OR (2007).

[24] D. Duchane and D. Brown, "Hot dry rock (HDR) geothermal energy research and development at Fenton Hill, New Mexico", Geo-Heat Centre Quarterly Bulletin, 23, Oregon Institute of Technology, Klamath Falls, OR (2002).

[25] T.W. Thompson, W.E. Coons, J.L. Krumhansl, and F.D. Hansen, "Inadvertent Intrusion Borehole Permeability", ERMS 241131. Sandia National Laboratories, Carlsbad, NM (1996).

[26] F.R. Walsh and M.D. Zoback, "Oklahoma's recent earthquakes and saltwater disposal", Science Advances, 1(5), e1500195, June 18 (2015).