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Borehole disposal of spent fuel and other high-level wastes: the case for deep, vertical, fully cased holes in saturated "hard" rock

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Driven by major advances in deep drilling technology and the geological understanding of the deep continental crust over the past 70 years, disposal in deep boreholes has moved from being technically unachievable to the point that it now offers a viable solution for the most hazardous nuclear wastes that could effectively be implemented "tomorrow"—i.e., within a few years. Moreover, disposal in deep boreholes is arguably superior in almost every respect to the mined and engineered repositories being pursued for high level waste by most countries. During the first 50 years of their evolution, almost all deep borehole disposal concepts shared five key aspects: (i) the hole was as deep as possible, (ii) it was vertical, (iii) it was fully cased, and (iv) it was in "hard" basement rock (v) saturated with aqueous fluid (groundwater). Technical advances in drilling over the last 20 years have encouraged proposed versions of the concept which depart from one or more of these aspects, but it is our contention that all five fundamental aspects should be retained. This paper summarises the more important arguments supporting this view. In order to meet the necessary post-closure (radiological) safety requirements, engineer out possible operational problems during construction and waste-package deployment, and capitalise on the main benefits of borehole disposal, the hole itself must be over 3 km deep, vertical, fully cased, and in suitably hard (ideally granitic) host rock saturated with aqueous fluid.

KEYWORDS
nuclear waste, geological disposal, deep boreholes, geological barrier, safety case

1 Introduction

Deep borehole disposal (DBD) is a viable alternative to mined repositories for the geological disposal of solid, long-lived, heat-generating, radioactive wastes, such as spent fuels (SF), vitrified waste from reprocessing, and other high-level wastes (HLW). Its technical readiness level is higher than is widely perceived (NND, 2022), and the consensus among international experts is that the only obstacles to its implementation are the need for a full-scale demonstration of borehole construction with non-active waste package deployment (IFNEC, 2020; Gibb and Beswick, 2021) and the establishment of national/international regulatory frameworks against which to set safety cases (Freeze et al., 2016; 2019; 2021). Current regulatory frameworks are designed for repositories and, while they would have much in common, are probably more conservative than necessary for DBD.

DBD offers many potential benefits over mined and engineered repositories, especially greater safety and cost-effectiveness, faster/earlier implementation and lower environmental impacts. Others benefits include modular (possibly dispersed) disposal, a flexible pay-as-you-go solution, temperature insensitivity, reduced post-reactor cooling and easier siting. These are discussed by Chapman and Gibb (2003), Brady et al. (2009), Arnold et al. (2011), Beswick et al. (2014), Chapman (2019), Cotton (2021), and Gibb and Beswick (2021).

DBD was initially considered as a solution for such wastes (albeit in liquid form) by the US National Research Council (1957), but the boreholes required were so far beyond contemporary technology that the concept was dismissed in favour of developing much shallower (200–800 m) mined repositories. However, as drilling capabilities and geological understanding of the deep continental crust advanced over the ensuing decades, seminal papers and reports resurrected and developed DBD (Woodward-Clyde, 1983; Julin and Sandstedt, 1989; Harrison, 2000; Chapman and Gibb, 2003; Brady et al., 2009; Driscoll et al., 2012; Beswick et al., 2014; Hardin et al., 2015; Gibb and Beswick, 2021). DBD is now recognised as a viable option by the IAEA and is being considered by Norway and other countries. Acknowledging its potential for safe, cost-efficient disposal, especially for countries with small inventories, the IAEA has established a Coordinated Research Project on DBD with 16 member states as signatories. This aims to support preparatory work toward a field demonstration and provide guidance to WMOs considering DBD as part of their national programs.

Throughout the above developments, five fundamental aspects of a borehole were specified, implied or assumed, namely:

i. as deep as technically feasible;
ii. as close to vertical as possible;
iii. fully cased;
iv. in "hard" rock (ideally granitic basement);
v. saturated with groundwater, at least in the disposal zone (DZ).

Some recent borehole disposal proposals depart significantly from one or more of these aspects. We contend, however, that all five are essential if DBD of heat-generating wastes is to provide the necessary post-closure (radiological) safety, engineer out potential operational problems (during construction and waste package deployment) and maximise the benefits of DBD. Below we present the principal arguments for this perspective.

2 Discussion

DBD is multi-barrier with engineered and geological barrier systems (EBS and GBS). Its great strength comes from disposal in a geological environment that has been physically and chemically isolated from the near-surface zone of fresh groundwater for millions of years and can remain so for longer than required for the waste to become radiologically safe. The only threat to this containment comes from disturbances to the GBS caused by borehole construction, waste package placement, and elevated temperatures around the DZ arising from decay heat. All are transient and would be restored by natural processes. The first two arise during the relatively short time the borehole would be open (1–2 years) and they would recover after sealing, probably on a similar time scale. The extent and duration of the third can be predicted and controlled through waste loading. Once natural processes have restored the GBS to its pre-disruption condition, the EBS becomes effectively redundant—a significant benefit that could be realised soon after sealing.

The main reasons for our contention are given below, with those relating to combinations of two or more aspects presented under the last relevant heading.

2.1 Why deep?

Geological disposal seeks to isolate waste from the human environment for as long as necessary for decay to render it safe. For the DBD of HLW, this means ideally interring it below any accessible zone of fresh groundwater and preventing its return to this zone for up to a million years. This requires that (i) the shortest possible return path from the top of the DZ to fresh (probably circulating) water is maximised and (ii) that the geological barrier in this interval is sufficiently retardant to migration of any radionuclides escaping from the EBS.

Mechanisms for radionuclide return through the GBS to the surface are diffusion and/or advection. The former is usually too slow to be of real concern (Freeze et al., 2019) and is generally considered to provide adequate isolation for the safety case of mined repositories, where the migration path back to the surface is an order of magnitude shorter than for DBD. Advection, however, depends on several factors, particularly the bulk permeability (hydraulic conductivity for saturated rock) of the GBS. For granite or gneiss, the rock itself is essentially impermeable, and bulk permeability is mainly a function of the size, number, spacing and connectivity of any fractures in the rock. It is known that bulk permeability usually decreases with depth and, while this varies throughout the continental crust, the deeper the hole, the more this property is likely to prove appropriate for (ii).

2.2 Why vertical?

Non-vertical boreholes proposed for disposal are usually deliberately deviated from vertical to enable the DZ to remain within a geological horizon, such as clay-rich sediment. Below are some of reasons why the holes should remain vertical.

2.2.1 Construction issues

Boreholes up to 3.66 m diameter and ~1,900 m deep were developed for US nuclear bomb testing between 1962 and 1992 and drilled with verticality control to enable the installation of long nuclear test packages (Rowe, 1993). For large-diameter holes requiring robust casing, "vertical and straight" has remained the perceived wisdom in the industry. Deviated, often near-horizontal, wells are now routinely drilled for hydrocarbon production, but drilling at the diameters required for most HLW packages must still be vertical. This is particularly so in the hard rocks that are the primary targets for DBD, as developing the thrust needed to load the bit is considered impractical except for near-vertical holes.

The early developments led to applications of deep, blind shaft drilling (BSD) for mine access and ventilation and prompted the design of casings and cementing systems for large diameters outside the norm for oilfield well construction. Typically, composite steel-concrete or reinforced steel casings are used with the heavy strings "floated in" because of the high loads. For non-vertical holes at the diameters involved, it would be difficult, if not impossible, to install such casing.

Where BSD is used in a DBD scheme (e.g., Gibb and Beswick, 2021), the casing must be cemented. At these diameters, this is best done in the annulus using the tremie method in stages to ensure support and sealing. This differs from the oilfield approach and needs verticality to ensure even distribution. For oilfield drilling of any borehole section, construction is more straightforward and cost-effective if there is no need for directional tools. Emplacement of the large diameter casing and its successful cementing, while difficult, are demonstrably feasible in a vertical borehole.

2.2.2 Package emplacement

Borehole construction and post-construction procedures fall into distinct operational and safety categories. During construction, risks are acceptable and can usually be overcome or remedied. Once the borehole is drilled, cased, dimensionally checked, and flushed clean, it becomes a nuclear facility entailing effectively zero risk during package emplacement and the post-closure period. Vertical boreholes eliminate or greatly reduce potential operational problems during deployment, such as packages becoming damaged or stuck above the DZ. The assistance of gravity (rather than having to overcome it) during emplacement cannot be overvalued, removing the need to apply extra downhole force and facilitating the centralising of the packages. Furthermore, it ensures the necessary distribution in the annuli of casing cements, any sealing and support matrix (SSM) used, and the main seals above the DZ. The SSM is a specially developed cementitious material emplaced with each waste package to provide physical support and protection against groundwater corrosion for the waste packages and borehole casing (see Gibb and Beswick (2021) for emplacement procedures for SSM and the main seals).

A concern sometimes raised for vertical DBD is that primary load stresses in the waste package stack could risk premature failure. Hydrostatic pressures in the DZ (~50 MPa at 5 km depth) are compressive and could cause ductile failure if they exceed the yield strengths of package materials. The weight of stacked packages creates additional compressive stresses, so they require alignment, and buckling failure must be considered. Finite element modelling of stacks subject to such loads (Golding et al., 2024) shows that (i) buckling failure is unlikely to occur and (ii) employing an SSM eliminates the risk of ductile failure without resorting to excessively thick package walls or load-bearing bridge plugs.

For the DBD of all but the smallest waste packages, the vertical borehole scenario is the most straightforward and the only really practical concept with current technology and experience.

2.3 Why fully cased?

Most DBD concepts require the borehole to be fully cased for the reasons below, with some schemes advocating perforated casing for the DZ (Beswick et al., 2014; Hardin et al., 2015; Gibb and Beswick, 2021).

2.3.1 Stability

An inherent risk in any drilling is borehole instability. Although significantly reduced in high-strength host rocks, there is potential for debris from the wall to cause problems. Moreover, anisotropic horizontal stresses promote breakout, creating a non-circular borehole and a less stable relaxation zone around the borehole. It is thus necessary to fully case any DBD borehole during construction to ensure it is completed without problems and to minimise further operational risks during the disposal process.

Hydrostatic pressures at DZ depths risk distortion of the large-diameter casing that could impede waste package emplacement. This can be avoided by using perforated casing throughout the DZ, which also enables the emplacement of SSM and their flow into the casing-rock annulus.

2.3.2 Waste package deployment

These operations must proceed safely with no (or absolutely minimal) risk to the packages. Possibilities that could damage the integrity of the package include becoming stuck during descent to the DZ (and not being readily recoverable) and being dropped before reaching its destination. The latter is discussed below. The main causes of the former would be (a) non-circularity, (b) post-construction deformation of the bore, and (c) wedging during descent by debris—all of which are highly likely in an uncased borehole. Post-drilling checking of the hole, with remediation if necessary, and the insertion of robust casing would eliminate (a). The smooth inner surface of the casing and adequate package clearances would provide an unobstructed passage to the DZ, and regular calliper checks between deployments would ensure that any deformation is detected before obstruction becomes a risk. Full casing would eliminate (c) by preventing ingress of rock debris to the inner bore, and for perforated casing, the hole size can be designed to ensure that no debris large enough to cause problems could enter.

2.3.3 Safety

A key consideration in the pre-closure safety case is a package dropped during emplacement. In freefall, constrained by hydraulic damping, such a package develops a predictable terminal velocity (Golding, et al., 2024). This enables analysis of stress distributions within the package following impact with the rock floor or the preceding package. Mathematical modelling and laboratory-scale experiments show that the terminal velocity (at typical downhole temperatures and pressures) would be only a few metres per second in fresh water (slightly less in brine). Finite element modelling (ibid.) shows that the packages will not fail upon impact at such speeds for envisaged DBD scenarios.

Important additions to DBD safety arise from the use of SSM (Beswick et al., 2014). The emplacement of calculated amounts of specially developed cementitious grouts (Collier et al., 2019) with each package is crucial. Laboratory-scale experiments at ~ 70°C (Collier, et al., 2016; Travis et al., 2023) show that the grout completely fills the two annuli between the package and casing and between the casing and the wall rock. Although still to be demonstrated down-hole, this highlights the necessity for, and benefits of, perforated casing throughout the DZ.

2.4 Why hard rock?

Lithologies usually considered for geological disposal are igneous or high-grade metamorphic (so-called "hard" or "high-strength") rocks, clay-rich sediments, or evaporites ("salt"). Although deep drilling is possible in any of these, only the first is really viable to host the DZ of a DBD for HLW because of the following factors.

2.4.1 Structural strength

To avoid borehole instability, exacerbated by the large diameters necessary for DBD, it is necessary to construct the holes in high-strength rocks. Clay-rich sedimentary rocks lack the necessary structural strength for deep holes, and salt is too plastic, with flow properties that would necessitate prohibitively heavy casing for DBD.

2.4.2 Hydraulic conductivity

Holocrystalline rocks like granite or granitic gneiss have very low specific permeabilities for the rock itself (typical fine-grained granite ranges from 10^{-19} to 10^{-22} m^2). Bulk values for fractured rock are typically two to three orders of magnitude higher at low pressures, but they decrease with pressure, becoming similar to the rock itself at ~200 MPa (Kranzz et al., 1979), corresponding to a depth of ~6 km.

2.4.3 Temperature insensitivity

Rocks formed at high temperatures, like granite, are insensitive to temperatures of a few hundred degrees Celsius unless extensively altered to clays and other hydrous minerals, and they retain structural strength until close to their solidus (~550°C). DBD in such rocks can therefore tolerate greater decay heat temperatures in and around the DZ than repositories, where temperatures are usually restricted to less than ~100°C by performance limits of their EBS. This enables higher waste loadings and/or less pre-disposal cooling—both important benefits of DBD.

2.4.4 Homogeneity

Plutonic intrusions or high-grade metamorphic basements tend to be homogeneous on a scale of metres over greater volumes than, for example, sedimentary sequences. This is particularly true of their bulk physical and chemical properties relative to disposal borehole diameters and distances beyond the DZ affected by perturbances to the GBS. An important consequence is that the volume of rock requiring characterisation for DBD is significantly smaller than for mined repositories. Additionally, because of the role and strength of the GBS, relatively few properties need determining for each borehole, principally:

i. host-rock lithology and homogeneity;
ii. locations of fractures intersecting the borehole;
iii. distances to any significant fractures or fracture zones along the length of the DZ;
iv. bulk rock permeability, vertical and lateral, and flow rates adjacent to the borehole;
v. groundwater chemistry and compositional/density variation with depth;
vi. residence ages of groundwater and variation with depth,

Much of the continental basement is formed by such rocks, which occur at attainable depths over much of the Earth's land area, making them potentially suitable for DBD.

2.5 Why saturated?

Almost all of the continental crust is saturated below a water table between zero and a few tens of metres deep. In exceptionally arid regions, the water table may be a few hundred metres—and very occasionally over 1 km—deep, but such situations are unlikely to be sustained indefinitely, especially given potential rates of climate change, let alone geological processes. It is almost inevitable, therefore, that any deep geological disposal of nuclear waste will be in saturated rock.

2.5.1 Barrier function

Deep basement groundwater geochemistry usually reveals long contact with its present host rock, with residence times of many millions of years. It constitutes a massive, effectively static, barrier through which radionuclides diffuse too slowly for them to reach the biosphere before becoming radiologically safe. During a thermal high, however, the waste decay heat could provide a driving force for upward convection, and it is essential that the safety case for any specific DBD demonstrates that the disposal depth and strength of the GBS are more than enough to ensure that no radionuclide-contaminated water could get close to the near-surface zone of fresh water (Freeze et al., 2016).

2.5.2 Physical and chemical properties

Near-surface onshore groundwater is normally fresh and can persist to depths of a few hundred metres, below which it becomes brackish as total dissolved solids (TDS) increase and it transitions to saline brine. The depth to brine can be less than 200 m (Reilly et al., 2008), but is usually approximately 500–700 m (Bloomfield et al., 2020). As the TDS continue to increase with depth, the brine develops a strong density gradient which enhances the stability of the system, especially when a stratification becomes established in which there is little or no transfer of material across the layer boundaries. Such groundwater systems are commonplace at the depths proposed here and, while not an essential factor for DBD, greatly strengthen the GBS by further damping convection during any thermal high (Freeze et al., 2019).

Furthermore, being in a density stratified groundwater environment adds a potentially important benefit for countries with a history of tectonic disturbance as this could render the GBS largely "earthquake-proof". Although seismic shear waves could destroy the integrity of any EBS, they would have no effect on the density stratification of groundwater. Consequently, the groundwater around the DZ into which any radionuclides escaping from the primary containment might migrate would remain isolated from the less dense overlying layers and far below fresh waters, so preserving the containment of the DBD. Noteworthy is the contrast with a mined repository, where failure of the EBS results in contamination of near-surface fresh water.

2.5.3 Phase changes

For the higher waste-heat loadings feasible for DBD, it is conceivable that peak temperatures in and around the DZ could reach over 200°C above the ambient geothermal gradient. It is essential that at no point does the temperature of the fluid exceed the liquid-to-vapour transition for water, as the pressures generated could damage the barrier systems and threaten the safety case. To guarantee that this cannot occur, no waste should be disposed of at hydrostatic pressures below the critical point of water (374°C at 22.0 MPa), which corresponds to a depth of ~2.3 km in fresh water. Allowing for a reasonable safety margin and possible future fluctuations in depths to the water table, we would recommend that no heat-generating waste should be disposed of at a depth less than 3 km.

3 Conclusion

Borehole disposal of HLW, including spent fuel, that generates significant amounts of heat should be in deep, vertical, fully cased holes in saturated high-strength rock. No such waste should be disposed of less than 3 km deep. The safety case for any such scenario must accurately model the effects of decay heat on the GBS and confirm that they could not threaten its integrity on the timescale necessary. Furthermore, it is likely that cost-effectiveness, siting, and environmental issues could make DBD the method of choice for many long-lived radioactive wastes.

Data availability statement

Publicly available data and results were used in this study with sources cited in the text.

Author contributions

FG: writing–original draft and writing–review and editing. JB: writing–original draft and writing–review and editing. KT: writing–original draft and writing–review and editing.

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Conflict of interest

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