Understanding Deep Borehole Disposal Technology in the context of Spent Fuel and High-Level Radioactive Waste Disposal: History, Status, Opportunities and Challenges

A two-day webinar, November 4th and 5th, 2020, sponsored by the
IFNEC Reliable Nuclear Fuel Services Working Group

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Webinar Questions Received and Panel Responses

Following the webinar, the large number of questions submitted by the attendees was distilled into twelve focussed questions. The panellists have worked together to respond to these questions and the responses below reflect a broadly consensus view. Where there were differing opinions, these are noted. The responses are the opinions of the panellists and do not necessarily reflect the views of the organizations for which they work.

The webinar panellists and presenters were:

- Patrick Brady, Sandia National Laboratories, USA
- Neil Chapman, Arius Association, Switzerland
- Geoff Freeze, Sandia National Laboratories, USA
- Fergus Gibb, University of Sheffield, UK
- Håvard Kristiansen, NND, Norway
- Vladimir Lebedev, OECD Nuclear Energy Agency, France
- Dirk Mallants, CSIRO, Australia
- Philippe Van Marcke, IAEA, Austria
- Chris Parker, Deep Isolation Inc, UK
- Karl Travis, University of Sheffield, UK

The Panel was moderated by Neil Chapman, who also compiled this document from material provided by the Panel.

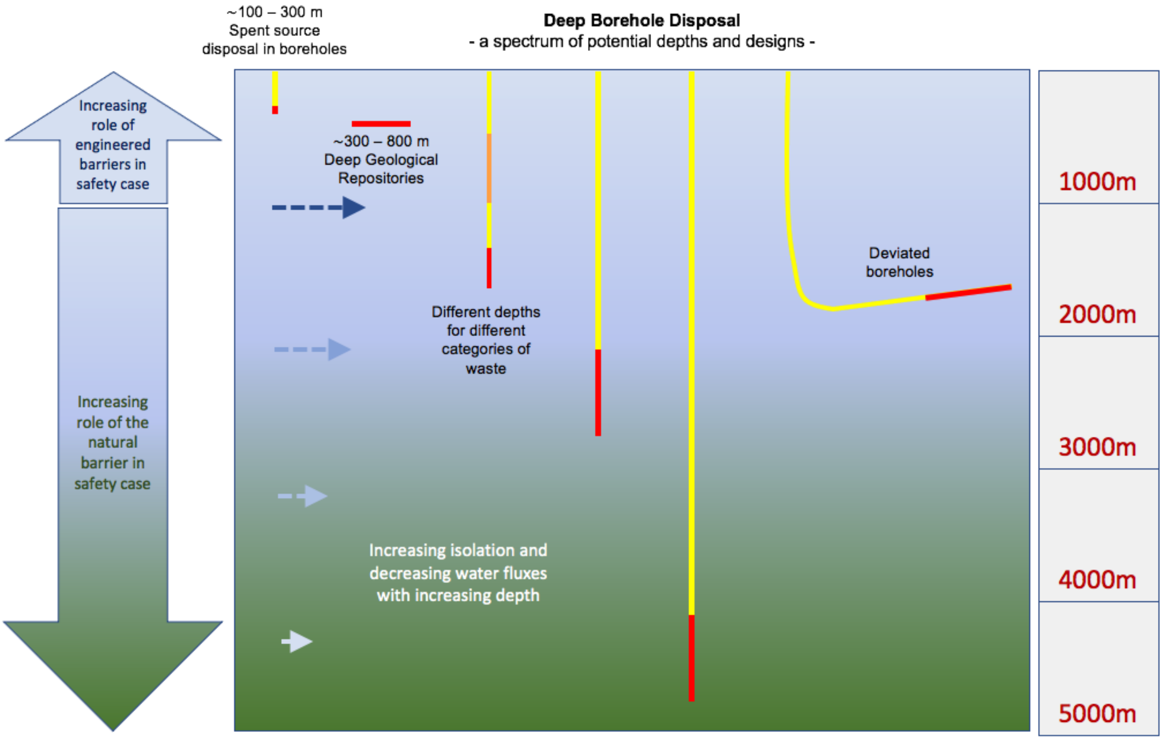
Frequently used acronyms are: DBD - deep borehole disposal; GD – geological disposal; DGR – deep geological repository; SF – spent fuel; WMO – waste management organisation; NPP – nuclear power plant; HLW – high level waste; HHGW – high heat generating waste; TRL – technical readiness level; FEPs – features, events and processes.

Preamble

The webinar focussed on the potential application of deep borehole disposal (DBD) in national programmes that are managing highly radioactive and generally long-lived wastes, such as spent fuel (SF) and high-level waste (HLW). A DBD facility would emplace wastes at considerable depth in a borehole some tens of centimetres wide in a suitable geological environment. The borehole would then be closed and sealed over many hundreds of metres of its length, perhaps up to several kilometres of its length, back to the surface.

There is not a unique concept for a DBD facility and many designs have been considered over several decades of development and evaluation. The figure below, based on the one used to introduce the webinar, provides some context. Panellists had a range of such concepts in mind when responding to questions.

What all the designs for DBD have in common is that the waste disposal zone within the borehole is *deep* – considerably deeper than any proposed mined repositories (deep geological repositories: DGR, which generally lie between c.300 to c.800 m depth). The greater depth of DBD enhances isolation of the waste but constrains the dimensions of waste packages compared to what can be emplaced in a DGR. As depth and isolation increase there is a reduction in the need for engineered barriers to provide containment, as indicated on the left-hand side of the diagram. Both DBD and DGR are variants of geological disposal and both provide the necessary containment of the wastes required to assure long-term safety.



An attraction of DBD is the potential to emplace wastes in volumes of rock that become increasingly hydrogeologically isolated with increasing depth, as shown on the diagram. This type of isolation is expected to come into play as depths begin to exceed, perhaps, 1500 m, but this is, of course, dependent on the geological environment and location. Some concepts propose considerable depths for the waste disposal zone, down to several kilometres – which has sometimes been referred to as *very deep borehole disposal* and is an approach favoured by several of the panellists. Some concepts propose using deviated (angled or sub-horizontal) boreholes to access a suitable host-rock environment in a particular geological formation, perhaps even at some distance from the disposal site. The important point emphasised by the Panel is that there is a spectrum of possible depths and designs for DBD that will depend on the waste inventory, local conditions, waste programme scheduling and other requirements of the user.

Since DBD could be used for several of the categories of waste that are generally being considered for disposal in a mined DGR, it is inevitable that some questions addressed by the Panel make comparisons between the two disposal concepts. In this context, the Panel felt it important to point out that there is not only a wide spectrum of possible DBD solutions available, but that some national waste management programmes might be optimised if they were to deploy a range of disposal facilities, amongst which DBD might play a part for some wastes in their national inventory.

1 Safety Case and Regulation

Are the safety strategy, safety case approach and regulatory expectations for DBD likely to be fundamentally different to a DGR or can we use mature approaches already available?

The elements of a safety case for geological disposal are the same, whether for a DGR or for DBD. They include a safety strategy (e.g., organization, management, design, laws and regulations, socio-politics, safety goals and functions) and an assessment basis (e.g., information/data supporting site selection, pre-closure, and post-closure). Safety assessments (e.g., pre-closure, post-closure, confidence enhancement) provide a “checklist” against which to evaluate the safety and viability of the disposal concept. The safety case methodology and approach should thus be the same and should follow mature structures developed by NEA’s IGSC, which have been developed over several decades. This means that a regulator should expect robust, systematic evidence of safety.

For DBD, certain safety case elements may require different levels of attention as compared to a DGR, but all elements must be considered. What will change for DBD are the safety functions and performance targets for the different system components. The safety strategy of a borehole repository will depend on the design and depth and could emphasize different safety functions. As indicated in the figure at the start of this paper, a DBD facility with disposal in a zone of hydrogeological isolation will rely more on natural barriers, whereas a shallower DGR or a borehole with disposal in a zone with hydrogeological connection to circulating groundwater may rely more on engineered barriers.

Consequently, there are differences in the weight of different parts of the safety case for a DBD facility and a DGR and a difference in the balance between the geological and engineered barriers. For a DGR a large part of the safety case focuses on the EBS and its components. For DBD concepts, it is reasonable to assume the unperturbed host rock and seals would provide most if not all the necessary containment, thus relaxing the requirements (i.e., contribution to long-term safety) for any additional engineered barriers. In DBD, this strong emphasis on the natural geological barrier, in the best cases, could render the EBS all but redundant, other than in the pre- and early post-closure stages.

For DBD, key elements of the post-closure safety case thus relate to deep hydrogeological characteristics, including the strength and performance of groundwater density gradients, duration and effects of thermal highs and recovery times from perturbations in the proximal and distal groundwater systems. These must be accurately determined and evaluated - requiring similar expertise, but different applications, to a DGR.

The pre-closure, operational safety case for emplacing waste packages in a deep borehole is different from that for a DGR with the former involving procedures most closely related to the oil & gas and geothermal energy industries, while those for the latter are more akin to the transport, tunnelling and mining industries. Demonstrations of pre-closure operations for DBD, with full radiation shielding, are not as advanced as for some DGR concepts.

Finally, it will be important in designing the DBD system and its safety case to use a proper, systems engineering approach based around a tiered requirements management system that incorporates safety functions, performance targets, design specifications etc. Perhaps the biggest need for DBD at the moment is an agreed safety concept, with safety functions defined for all the key components. This should be a focus for future work.

2 Demonstration

What are the key factors that a DBD demonstration test should address? As it is not possible to 'visit' the engineering underground (which is possible in a DGR), how should the DBD system be communicated and shown to people?

The issues that a demonstration needs to address fall into two general categories, with the first being perhaps of the highest priority:

- concerns about the viability of the concept and operational safety: the basic engineering issues of whether or not large enough boreholes can be sunk to required depths and whether non-active, simulated waste packages can be emplaced (and retrieved) easily, safely and repeatedly without problems: these are largely civil engineering matters;
- measuring and sampling deep hydrogeological and hydrogeochemical conditions in relation to safety cases and testing other aspects of DBD such as radiation protection at the wellhead, sealing the packages into the disposal zone and sealing methods to isolate it from the rest of the borehole, with the demonstration borehole becoming a surface and underground research laboratory.

As a minimum, a DBD test will need to demonstrate that radioactive waste can be safely disposed of in a borehole by:

- drilling and completing a borehole to target depths and diameter
- sufficiently characterizing the geological formations surrounding the borehole;
- safely emplacing and retrieving dummy waste packages;
- evaluating the effectiveness of plugging and sealing materials and processes; and
- undertaking total system performance assessments showing conformity with applicable radiological safety criteria.

A key component is the demonstration of the surface handling of non-active waste packages and waste emplacement workflow (i.e., with all necessary methodology for radioactive materials handling) and technology under controlled conditions (initially at the 'engineering' scale, but ultimately at the 'full' scale).

Techniques such as logging, coring and sampling, and downhole geophysics, which are fairly routine at shallower depths, need to be adapted or improved for the depths of a disposal borehole. This characterisation information for a disposal borehole is the foundation for a robust 3-D picture of the geological environment and its inherent isolation and containment properties.

A demonstration facility could be developed from pre-defined regulatory requirements for the safety case.

A specific consideration is whether some or all of the tests could be done in a borehole that is subsequently used for disposal, and whether this would reduce project risks, costs and time. While it might make good logistical and economic sense to subsequently use a successful test borehole for actual waste disposal, this could prove societally and politically difficult, in that gaining acceptance for a demonstration site could require a commitment that is not used for disposal.

Apart from clarifying current uncertainties (as in many of the points above), a vital function of a demonstration is to bring borehole disposal to life in as visual and transparent a way as possible, communicating with as wide a range of interested stakeholders as possible. Hence there is a need for, for example, full sized mock-ups of casing, tools and EBS that people can see, touch and maybe even hold. These can provide a sense of the reality, even though they cannot be accessed underground.

Physically visiting a deep borehole repository will necessarily be limited to any surface infrastructure, although not much infrastructure may remain once the hole has been sealed. There are opportunities to visit the borehole site throughout its development (drilling of exploration and disposal hole, waste insertion – and reversal, if required, and seal emplacement), although strict health and safety requirements will mean this will need to be from a safe distance.

Once the borehole has been drilled and the emplacement tests completed, there are opportunities to continue to communicate various features of the borehole via so-called virtual twins. A virtual twin is a digital representation (parallel virtual model) of the physical structure (the borehole, the dummy waste canisters, seals, monitoring devices that send data to a central database, and the geosphere that surrounds the borehole), linked to data from the site characterisation and ongoing monitoring, and results from simulation modelling (e.g., evolution of heat release over time). Such information can be made available through interactive digital media for both a technical and less technical audience. It also provides a means to facilitate knowledge management, enhance scientific collaboration and training.

3 Reversibility

Is DBD intended principally to be an irreversible, irretrievable option? How might a retrievability policy need to be adapted to the much shorter open, operational periods of DBD compared to DGRs? How long would you expect a long horizontal hole to maintain a capability to retrieve? Would nuclear safeguards provisions need to be adapted for DBD?

When DBD was originally being discussed, in particular in respect of potential disposal of surplus fissile materials, an attraction was that the concept met the 'practically irrecoverable' requirement of nuclear safeguards. Since that time, and with the focus being principally on geological disposal in mined repositories, several countries have adopted a policy of reversibility for the implementation of DGRs and the question has arisen whether this policy should/could also apply to a DBD facility.

Disposal packages can be safely retrieved from a borehole repository during the operational period and – if desired – for a number of years in a pre-closure phase following initial emplacement. The ease with which this could be done is again likely to be dependent on the design of a DBD facility. One panellist considered that retrieval can be done more easily from a horizontal borehole concept - but others disagreed, considering that working in a horizontal hole brings its own handling problems compared to deploying well-tried methods used more routinely in vertical holes: however, the Panel as a whole considered that retrieval in the operational period is feasible from all types of borehole design.

Retrieval of objects (such as logging tools) from deep boreholes is routine in the drilling industry, including retrieval of items that are stuck or jammed. Deep Isolation has made a first demonstration of the retrieval of a prototype nuclear waste disposal canister at Schlumberger's demonstration facility in Cameron, Texas. This test was largely intended to demonstrate the practicality of retrieval techniques in a sub-horizontal borehole and will eventually need to be repeated on a design-specific basis at actual waste package scales and tolerances for specific DBD designs.

This simple retrievability cannot continue indefinitely. At some point - dependent on the conditions for a given site - the cased borehole integrity may be compromised by the effects of regional stresses on the host rock. Understanding regional stresses and modelling borehole stability will be part of siting and critical in the development of an operational timeline for each repository.

Against this background, it is clear that further discussion and collaboration is needed to reach consensus on the objectives of regulatory policy in respect to borehole retrieval – and hence on:

- the length of the post-emplacement but pre-closure time frame that should be required; and

- whether retrievability should be a requirement in a post closure scenario - when it will still be possible with either vertical or horizontal boreholes (for example by piloting down the sealed access path and re-establishing a cased route to the surface) - but will be expensive and pose significant operational difficulties.

The consensus view of panellists is that:

- A major benefit of all forms of geological disposal is its ability to put radioactive waste deeply underground where it is isolated from the biosphere and human activities, with all the nuclear safeguarding and non-proliferation benefits this brings.

- If retrievability is a necessary part of a national policy for all forms of GD, the focus for both DBD and DGR disposal should therefore be on 'reversibility until final closure' – enabling both the completion of emplacement and an appropriate period of pre-closure monitoring. Both DBD and DGR should therefore be seen as permanent disposal operations, for which century-scale retrievability requirements are inappropriate.

- This sets different retrievability timescales for each: months/years for a DBD repository and decades for a DGR.

- Dialogues on reversibility and retrievability can contribute to the understanding and eventual ownership of the concept by a larger part of society.

4 Economics

DBD is estimated to be more economical for disposal of small inventories. What size of HLW inventory makes it more economic to move from DBD to a DGR? For example, how much would the UK save if all of its HHGW waste were to be emplaced in a DBD?

The very high fixed costs of a DGR mean that the lower cost, modular nature of boreholes makes DBD particularly attractive for small volumes of waste. The table below illustrates this cost advantage of DBD over DGR disposal in the case of a small volume of research reactor SF.

Comparing the costs of DGR and DBD disposal for a small volume research reactor (SF) - data and analysis based on Chapman and McCombie (2019).

	The DGR option	***The DBD option***
Costs	• **The average estimated cost internationally of disposing of NPP-SF in a conventional DGR, including all the necessary siting, RD&D and support functions, is around 1 M** USD/tHM (Chapman, 2018). The range of estimated costs internationally varies from around 0.4 to 1.5 MUSD/tHM, with economies of scale reducing unit costs as inventories increase. The smallest national inventory of NPP-SF for which DGR costs have been estimated in detail is that of Slovenia. Disposal costs for 926 tHM SF were estimated at around 650 MEUR (taxes and compensation payments excluded), or 0.8 MUSD/tHM. • Extrapolating from such data, **the total fixed cost for a DGR for research reactor SF is about 1.1B USD** (assuming most of the cost for RD&D, design and administrative costs can be saved using available experience and DGR technology) and the **cost per tHM is 0.4 M USD**.	• **The most comprehensive peer-reviewed DBD cost assessment to date is from Arnold et al. (2011).** This focuses only on waste packaging (for HLW/SF), borehole operation and sealing costs for a vertical borehole. For a 0.32-m diameter, 5 km borehole disposing around 250 tHM in approximately 400 canisters, findings were: ▪ Total disposal cost = 55 MUSD ▪ Cost per tHM = 0.22 MUSD, reducing to 0.16 MUSD for subsequent boreholes at the same location
Conclusion	The unit costs of disposal in a DGR for small volumes of waste rise significantly if there is no benefit from economy of scale	If a single deep borehole can accommodate all the research reactor SF at a cost of 55 MUSD (Arnold et al 2011), then these values compare favourably with the 1.1 BUSD total fixed cost and 0.4 to 1.5 MUSD/tHM for a DGR.

Traditionally, it has been assumed that these cost advantages for DBD will reduce in the case of large inventories of SF/HLW – and also in the case of more heterogeneous inventories that include other wastes that require geologic disposal but are intrinsically formed in ways that are not appropriate for borehole disposal. ("If we need to build a DGR anyway, why not use it for all our relevant waste?")

Increasingly, however, DBD is being considered as a potentially important part of a cost-effective solution even for large, heterogeneous inventories:

- **In the ERDO case study** presented at the webinar, in developing its concept for a multi-national European repository ERDO is exploring the benefits of using lower cost DBD for HLW/SF, alongside a nearer-surface mined repository dealing with other waste streams.
- **In the UK case study** presented at the webinar, up to 11% of the total inventory identified by the UK government as requiring geologic disposal was found to be suitable for borehole disposal - comprising all the High Heat Generating Waste. Estimating the cost savings that might be possible if all of this HHGW were to be disposed of in boreholes rather than in the UK's planned Geologic Disposal Facility (GDF) was outside the scope of this preliminary study, although they are potentially significant. As discussed on the webinar, further work is needed across a range of regulatory, geologic and operational issues to explore this, and no decisions have been taken at this stage by the UK government in relation to borehole technology.

5 Siting and site characterisation

Is it correct that DBD opens up a much wider range of siting options than a conventional DGR? How much site characterisation is actually necessary for DBD, compared to a conventional DGR and would site investigations be more demanding for long horizontal holes compared to vertical holes?

Most studies of DBD suggest that it would require less site characterisation than for a DGR and that this, along with fewer key geological criteria for a technically suitable site, should make it easier to site a DBD facility than a DGR. It has also been proposed that some of the potential benefits of DBD should make it more publicly and politically acceptable.

With a very small footprint and a much smaller volume of the disposal zone, a deep vertical borehole requires a considerably smaller volume of suitable rock than a DGR. This in itself makes it more likely that a technically suitable site can be found. The central geological guidelines for siting a DBD facility are:

- a stable host rock with a very low bulk hydraulic conductivity;
- a relatively low-anisotropy regional stress regime;
- old, stratified saline groundwater with sufficient density at the disposal depths to ensure isolation from near-surface groundwater;
- an environment in which it is possible to forecast with confidence that these conditions will continue to prevail over the timeframe of the safety assessment.

Most geologists believe that the first three conditions exist at depths of a few km over large parts of the continental crust**:** a view that is consistent with the evidence from the relatively few boreholes that have actually investigated the geology and hydrogeology at such depths (see, for example,[1],[2]). On the other hand, geophysical and geochemical evidence indicates that the continental basement is far from uniform, raising the question of just how widespread the key conditions for DBD really are throughout the crust. The answer is that we do not actually know. Clearly, suitable conditions do exist in many places, but we do not yet know enough about the continental crust below the top km or so in most areas to make quantitative estimates about how much of it might be geologically suitable for DBD. Nevertheless, even if the proportion of the continental crust suitable for DBD turns out to be less than anticipated, it is very unlikely to be less than for DGR.

[1] Fehn U and Snyder GT (2005) Residence times and source ages of deep crustal fluids: interpretation of 129I and 36Cl results from the KTB-VB drill site, Germany. Geofluids 5(1): 42–51.

[2] Bucher K and Stober I (2000) The composition of groundwater in the continental crystalline crust. In Hydrogeology of Crystalline Rocks (Stober I and Bucher K (eds)). Kluwer, the Netherlands.

One panellist observed that an unfortunate consequence of the focus on the relative benefits, like ease of siting, for the two disposal concepts may be to draw attention away from the fact that there are alternative, safe, disposal concepts for HHGW that give WMOs the option of evaluating which best suits their circumstances.

The amount of characterisation required for both DBD and DGR depends on the relative importance of the various elements and FEPs in the safety case and safety assessment. The significant characterisation efforts that are required (and have been made) for DGR, particularly to understand flow in fractured rocks, arise because of the relatively shallow depths at which they are located. At depths of a few hundred metres the hydrological system is dynamic, responsive and often connected, however distantly, to near surface water supplies. Consequently, flow rates and volumes are critical to the safety case and uncertainties need to be well understood and scoped. For DBD, the greater depths result in longer transport pathways to the biosphere and lower permeabilities as open fractures are few at such depths. DBD will therefore require less detailed information about fractures and fault zones. Instead, the focus is on hydrogeochemical indicators of hydrodynamic immobility and stability.

It is often suggested that, for deep vertical borehole disposal, a single, small diameter, borehole would suffice for characterisation. While this may be enough to rule out a site, it is unlikely to be sufficient to confirm suitability. Some of the Panel have pointed out that characterisation is needed on two scales, the borehole scale (i.e., immediately adjacent to the hole along the length of the disposal zone, if not the entire hole) and on the sub-regional scale. However, most of the Panel agreed this requires nothing like the effort needed for a DGR and would probably require only a small number of additional holes following a positive result from an initial characterisation borehole.

Because of the greater depth and difficulties of access for sampling, obtaining accurate, representative data under more extreme geoscience conditions will be challenging. Notwithstanding this, the much smaller volume of rock to be characterised and the lesser extent to which characterisation is necessary, led the Panel to expect that site investigations for a DBD would be less demanding on resources and take less time to complete than for a DGR.

Interestingly, it was noted that for a multi-hole DBD programme the number of characterisation boreholes required does not increase much with the size of the programme since each disposal hole produces further data about the conditions at depth.

The greater depth and isolation of DBD and the much reduced footprint and environmental impact would intuitively suggest it should be easier to site than a DGR from the perspective of public and political acceptability. However, the Panel did not offer a view on this beyond**:**

- observing that Cotton (2017), in his book *Nuclear Waste Politics*, believed this to be the case and advocated DBD as the most likely way of gaining public acceptance of radioactive waste disposal facilities, and
- noting that societal and political acceptance is often the limiting factor in siting any disposal facility and that this could reduce the importance of technical (and presumably economic) differences between disposal concepts.

On the comparison between the characterisation required for deep vertical boreholes and long, deviated, horizontal holes, the Panel noted that this will be highly dependent on the geological environment being investigated. For a vertical borehole facility, it might be expected that most of the site characterisation requirements would be met by the deep borehole itself (or a pilot hole). Depending on the location and geological environment, there could also be a requirement to characterise geological structures local to the borehole, but extending some distance from the site (e.g., steeply dipping brittle fracture zones). This would be done largely by using surface-based geophysical techniques. Horizontal boreholes that extend some kilometres from the site, whilst also gathering data predominantly from the borehole itself, would need to investigate structures over the wider footprint being accessed, which could be significantly larger than for a vertical borehole facility. Again, this would be expected to be done using conventional surface-based geophysical techniques but might also require additional characterisation boreholes some distance from the facility.

The overall conclusions of the Panel are that:

- DBD is expected to open up more siting options than DGR;
- the amount and extent of characterisation required to make the safety case for the former is expected to be substantially less than for the latter, although this will be influenced by the eventual nature of the safety case and associated regulatory requirements.

Together, DGR, vertical DBD and horizontal DBD present access to a great range of siting possibilities and offer considerable flexibility in repository design.

6 Vertical and horizontal DBD

Some aspects of horizontal borehole seem more problematic than vertical holes: the potential for jamming; general hole construction technology; simplicity of a single 5000 m vertical hole for all the Hanford capsules; longer term stability of vertical holes to lithostatic load etc. Where is the evidence that deep borehole costs accelerate much faster with depth than horizontal holes do with length?

As discussed during the webinar, there is no single right design for a deep borehole repository, and the optimal choice will vary according to the specifics of site geology and the inventory to be disposed of. There are advantages and disadvantages to the different designs.

Although there is longer industry experience with traditional vertical boreholes for oil and gas, and geothermal energy, directional drilling is routine in the oil and gas industry: there have been approximately 120,000 horizontal wells drilled in the United States alone since 2007[3]. The technologies for horizontal borehole construction, and how to place and retrieve tools from horizontal wells, are well known.

In terms of cost comparisons between horizontal and vertical, the Panel is not aware of any published studies on this. Broadly speaking, Deep Isolation expects costs to increase at a faster rate as the borehole goes deeper, but that the costs of extending horizontally increase on a more linear basis. This is driven by the way that very deep vertical holes tend to penetrate multiple formations and cross multiple geological barriers. This increases the cost and complexity of drilling and also requires additional investment in casing – resulting in a significantly increased borehole diameter at the surface. However, there was uncertainty expressed within the Panel and these expectations need to be examined in more detail in the future.

In this respect, additional published cost analysis would be helpful for stakeholders when making cost comparisons, and Deep Isolation is urged to publish further detail and supporting evidence. For example, it was pointed out by panellists that, while there is a paucity of data on the costs of deep, large-diameter vertical boreholes, there is good data of drilling costs for deep geothermal wells, oil and gas wells, and CO_2 geological sequestration wells, with reviews showing that predictability of costs is reasonably accurate for the 1 – 5 km depth range, mainly based on geothermal wells. The cost-depth

[3] See https://www.eia.gov/petroleum/wells/, Figure 2. Figure notes approximately 140,000 wells in 2018 less approximately 20,000 wells in 2007 for 120,000 horizontal wells.

relationship is often described by means of a quadratic equation: costs at 5 km are only 2.4 times greater than at 2.5 km.

The example of Hanford capsules[4] is interesting, since they are less than 9 cm in diameter and less than 60 cm long. This would entail a horizontal disposal section for the borehole that was similar in diameter to typical horizontal wells drilled frequently by the oil and gas sector. If it were assumed that each canister was spaced 60 cm apart in the horizontal section, it would still only be 2.3 km of horizontal disposal length and require one borehole. Including multiple packages in one disposal canister may reduce the spacing and horizontal distance. If a horizontal borehole disposal site had a strongly-isolated rock layer 1 km from surface and had a 2.3 km disposal section, there would be a total borehole length of 3.3 km.

For comparison, a single vertical borehole with a 31 cm standard oilfield diameter could accommodate the Hanford capsules in a 544 m long emplacement zone. With 2 km of engineered seals, and an additional 1 km of borehole fill material overlying the seals, the waste could be isolated in an emplacement zone 3 – 3.5 km deep. This is of course highly dependent on finding the right site and on canister spacing assumptions. A more formal analysis of this example would be needed for a specific situation to determine if a vertical borehole design and/or a horizontal borehole design would provide a safe and feasible solution.

On a broader horizon, the Panel observes that, when discussing economics, it is important to consider not just the cost of the technology (i.e., shallower horizontal borehole vs. deeper vertical borehole vs. DGR) but also the overall cost of a national waste management programme. The life cycle costs associated with a national programme, in addition to the disposal facility costs include management, waste storage, waste transportation, general R&D, site characterization, site selection, multiple stakeholder and regulatory approvals, and final licensing. Thus, while the cost differences between vertical and horizontal boreholes at diameters sufficient to accommodate radioactive waste may not be well documented, the differences are likely to be small relative to the overall programme costs.

7 Capacity of a DBD facility

How many holes would it take to hold all the fuel from a full lifetime of operating a typical large NPP?

Geological disposal in deep boreholes is a versatile solution for high level radioactive waste and spent fuels and may be particularly suited to those countries with smaller inventories. The question of how economical DBD would be is related to how many boreholes would be required to dispose of a given amount of waste/fuel, and this is the question the Panel set out to address.

Panel members agreed that the number of boreholes required depends on several factors, mainly: depth and diameter of the hole and the nature of what is being disposed of. The requirements for spent fuel being very different from those of HLW, for example.

For spent fuel, the number of boreholes required can be significantly reduced if, instead of disposing of complete fuel assemblies, the fuel rods are removed from a number of assemblies and inserted into a single disposal container at a packing density as close to the maximum theoretical number as practical. Such a process is known as consolidated disposal. For example, consider the disposal of whole PWR assemblies versus consolidated disposal for AP1000 fuel rods. A single PWR assembly would fit into a container of outer diameter (OD) = 0.36 m (internal diameter, ID = 0.32 m) and length = 4.640 m. With a container of these dimensions, a casing OD of 0.454 m could be used and a borehole with a diameter

[4] The Hanford capsules referred to contain principally recovered ^{137}Cs and ^{90}Sr and have high specific activity. See, for example: https://www.osti.gov/servlets/purl/1365044

of 0.56 m in the disposal zone. For a deep vertical borehole drilled to 5 km depth with these dimensions and a DZ of 2 km, a maximum of 400 containers could be disposed of per hole (this allows for a support matrix and any necessary bridge plugs).

A typical PWR NPP producing around 1500 tHM over an operating lifetime of 60 years would therefore require 6.6 (i.e., 7) boreholes at one assembly per package[5]. However, removal of the fuel rods and consolidation, enables the equivalent of just over 3 assemblies per container, reducing the number of holes by a factor of 3, i.e., 2.2 (so only 3 boreholes, not necessarily all to full depth, are required). Panellists pointed out that there is, however, significant cost and an added worker risk associated with rod consolidation, particularly if existing canisters need to be reopened.

The Panel suggested that DBD might also be considered a cost-effective disposal solution for small volumes of intermediate level wastes. Examples include research reactor spent fuel and vitrified waste from the reprocessing of spent fuel from research reactors. For the lifetime of two research reactors (10-20 MW each, 50 years of operation), approximately 100 vitrified waste canisters (180 L each, 1.34 m long) would be generated. These could fit in a single borehole and this would only need a disposal zone of a few hundred metres.

Disposal of vitrified high-level waste by DBD was also discussed by the panel. The 2019 BEIS/NDA inventory of vitrified HLW from reprocessing of spent fuel predicts a UK responsibility for 7660 containers by the end of reprocessing and vitrification. Much of this is already packaged in steel containers with OD of 0.43 m and a height of 1.35 m. However, it has been suggested that these might require an overpack owing to the thin walls of these containers (5 mm thickness). An overpack with at least 1 cm of thickness would have an OD of 0.45 m and a length of 1.39 m. Each of these containers holds 450-500 kg of vitrified product. Working on the assumption of readily available borehole casing sizes from the drilling industry, a single borehole drilled to a depth of 5 km, with a 2 km disposal zone of 0.61 m diameter, could be used to dispose of 1280 vitrified HLW containers[6]. The entire inventory of 7660 containers could be disposed of in as few as six such boreholes. Thermal modelling calculations suggest deep vertical boreholes could be spaced as little as 50 m apart in a multi-borehole disposal site, giving a footprint similar to a standard football pitch.

8 Oilfield technology

As DBD is based on oilfield technology developed for drilling in sedimentary rocks, does moving to a crystalline basement rock environment create problems? Cementation is a recurrent problem area for oilfield boreholes: would this also be a major issue for meeting the requirements of a DBD facility?

There are some significant technology overlaps between geothermal drilling (often in crystalline rock environments) and oil and gas drilling in sedimentary formations. For example, the polycrystalline diamond drill bits used to drill through sedimentary rocks for oil and gas were originally developed by Shell and Sandia specifically to drill through hard, crystalline rocks in geothermal areas.

Vertical holes in granite are based on geothermal drilling technology (typically around 24.5 cm or 9.6 inch diameter) rather than on oilfield technology, although oilfield-size tools are readily available to drill at moderate angle built-up rates in almost any direction. Horizontal holes in shales use oilfield technology. Large diameter wells in crystalline rocks can be drilled, 16 (41 cm) or 18 inch (46 cm) is readily available, increased diameters can be drilled by using, for example, hole openers. The Has

[5] F. G. F. G. Gibb, K. P. Travis and K. Hesketh, "Deep Borehole Disposal of Higher Burn-up Fuels", *Min. Mag.,* 76(8), pp. 3003-3017 (2012).

[6] A. J. Beswick, F. G. F. Gibb and K. P. Travis, "Deep borehole disposal of nuclear waste: engineering challenges", *Energy*, 167(2), pp. 47-66 (2014).

Innova Rig from Anger & Söhne AG in Germany has drilled a 0.66 m diameter hole in granite down to 1.3 km. However, borehole stability will be an issue and excellent fluid pressure control and smart casing and cementation may be needed depending on the expected lithology and formation pressure.

Oil and gas wells use advanced cementation technology to avoid contamination of rock formations and groundwater. Current technology uses multiple barriers (multiple casings with cementation of annuli along the entire well). Well failure or loss of well integrity may result from a well breach (or number of well breaches) and can take the form of a hydrological or environmental breach. The three types of breaches are defined as:

- Well breach – failure in cement, casing, downhole and surface sealing components
- Hydrological breach – fluid movement between different geological units, or
- Environmental breach – fluid leaks at surface and causes contamination of water sources.

It should be noted that occurrence of the above failure mechanisms for a particular well does not necessary lead to lost integrity of the well: i.e., a hydrological or environmental breach. This would depend on the extent of the failure mechanisms along the well and specific geological conditions. Example well failure rates are based on data from conventional oil and gas wells in Ohio and Texas, USA: estimates of well barrier failure (well breach) rates ranged from 0.035 to 0.1% for a well population over 250,000, whereas complete well failure (hydrological or environmental breach) rates are estimated to be one order of magnitude lower.

At present the eventual safety case requirements for the durability and longevity of borehole seals, sealing materials, cementation and casing, are open issues for discussion and are likely to be concept, design and location specific. Panellists noted that recent calculations of post-closure DBD safety[7, 8] show that even if these and other elements of the EBS fail on the first day of repository closure, the long-term post-closure safety case is not likely to be significantly impacted.

9 Disposal containers

Do these have to be designed to resist high load pressures and what factors of safety might be needed? Do they need to have high corrosion resistance (e.g. Alloy 625) or would the DBD safety concept not demand this?

DBD is a multi-barrier form of geological disposal for which all elements of both the geological and engineered barrier systems can contribute to the safety case. However, under appropriate circumstances the natural geological barrier of a DBD facility may be so robust that the contribution required of the EBS to long-term system safety is minimal. This question asks about the extent to which a major component of the EBS, the waste package itself, would be required to provide a safety function.

The primary function of the waste package (whether a single container or one or more containers within an overpack) is to contain and protect the waste during the operational phase and the Panel agrees that this is essential, at least up to the point that the borehole is sealed (closure). Some panellists observed that preliminary, generic, post-closure assessments (e.g., see references in Section 8) have shown that, even with no credit for the waste package (i.e., it is assumed to have no post-closure safety function), long-term radionuclide transport away from the disposal zone of a deep vertical borehole is slow. This could be taken to imply that no post-closure safety function is needed from the package.

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[7] Finsterle, S. , Richard A. Muller, John Grimsich, John Apps, Rod Baltzer. Post-Closure Safety Calculations for the Disposal of Spent Nuclear Fuel in a Generic Horizontal Drillhole Repository, Energies 2020, 13, 2599; doi:10.3390/en13102599; available online at https://www.mdpi.com/1996-1073/13/10/2599

[8] Finsterle, S., Cal Cooper, Richard A. Muller, John Grimsich, John Apps. Sealing of a Deep Horizontal Borehole Repository for Nuclear Waste, (currently in peer review, for publication in Energies)

However, the consensus view of the Panel is that the integrity of the waste package should be maintained until any perturbations in the local and regional geological barriers, especially in the hydrogeology, caused by the drilling, operational activities and, possibly, the thermal pulse arising from waste decay heat, have been restored to their original, stable, state by natural processes. Heat flow models indicate that the thermal high, seen as the principal (and longest lived) cause of perturbations, generally lasts for between a few decades and a few centuries[9, 10] and possibly up to a thousand years O'Brien et al. (1979), depending on the types of waste being disposed of.

To fulfil its primary function and last beyond the duration of the thermal high, the waste package must be able to withstand the hydrostatic pressure at the maximum depth of disposal and, in the case of vertical holes, load pressures from the stacking of packages. It must also be able to resist corrosion failure in a hostile, probably chloride-rich, chemical environment. Several packages suitable for the DBD of HLW & SF have been designed to meet these criteria. Stress analysis of the stainless steel 309 package proposed by the DBD Research Group at the University of Sheffield shows it can, on its own (i.e., with no contribution from its contents), withstand a hydrostatic pressure of 50 MPa with a safety factor of over 1.3 and vertical loads over 150,000 kg with a safety factor greater than 3. The German BSK austenitic steel disposal container[11] can withstand a maximum load of 61 MPa at a disposal depth of 5,000 m. Given that few, if any, deep borehole disposal scenarios would require the integrity of the waste package to remain intact for over 1000 years after closure of the borehole, it is the view of the Panel that appropriately selected steels or stainless steels would provide more than adequate corrosion resistance and there is no need for special high pressure, high temperature or corrosion resistant metals or alloys.

One panellist added that both the mechanical strength and the corrosion resistance functions of the waste package could be substantially increased by the use of sealing and support matrices in the space between the package and the borehole wall[12, 13].

Some of the Panel indicated that, for shallower or horizontal boreholes, a greater safety contribution may be required from the EBS, especially containment by the waste package, to provide a more significant safety function over a longer term. In such cases, longer-lasting, corrosion resistant materials might be advantageous. Nevertheless, generic performance assessments calculations of even relatively shallow (1000 – 1500 m depth) horizontal borehole repositories illustrate the primary safety function of the geosphere[14] using both sensitivity analyses and evaluations of disruptive scenarios involving early canister failure and instantaneous waste mobilization. These analyses show that the geosphere alone provides sufficient, passive protection over the entire performance period.

In conclusion, the view of the Panel is that waste packages must be able to resist combined hydrostatic and load pressures and corrosion to fulfil their operational and safety functions. These properties are mainly be required for as long as there are significant perturbations in the geological barriers due to the drilling or the waste that is emplaced. This period is expected to last for less than 1000 years after closure of the borehole.

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[9] Gibb FGF, Travis KP & Hesketh KW. (2012) Deep borehole disposal of higher burn up spent nuclear fuels. Miner. Mag., 76(8), 3003-3017

[10] Arnold BW, Brady P, Sutton M, Travis K, MacKinnon R, Gibb F & Greenberg H. (2014) Deep Borehole Disposal research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals. Report SAND2014-17430R for US DOE, Sandia national Laboratories, Albuquerque, NM. USA.

[11] Bracke, G., Charlier, F., Liebscher, A., Schilling, F., Röckel, T. (2017): About the Possibility of Disposal of HLRW in Deep Boreholes in Germany. - Geosciences, 7, 3.

[12] Gibb FGF, McTaggart NA, Travis KP, Burley D & Hesketh KW. (2008) High density support matrices: key to the deep borehole disposal of spent nuclear fuel. J. Nuclear Materials, 374, 370-377.

[13] Collier NC, Milestone NB and Travis KP (2019) A review of potential cementing systems for sealing and support matrices in deep borehole disposal of radioactive waste. Energies, 12(8), 2393 http://doi:103390/en12122393

[14] Finsterle et al., 2020 and in press: op cit

10 Potential users

What types of national radioactive waste management programme are the most likely users of a DBD facility and would it be integral to or separate from their main programme?

The presentation made at the webinar addressed this issue and was based on an article published in 2019[15], which concluded that the decision on whether to consider DBD is almost entirely a strategic matter, rather than one based on safety or any other technical requirements. The article suggested that the following types of user country might be likely to give DBD serious consideration – possibly for the reasons stated:

- Countries with major historic nuclear development, extensive fuel cycle facilities and complex waste inventories: the major drivers might be lack of progress with a DGR coupled with the need to show achievement in the national waste management programme, or a desire to deal with a specific waste stream (especially excess fissile materials such as separated Pu), possibly using a solution local to the source of the waste. Such countries would also be expected to have the resources and the technology to move forward with DBD.
- Countries with small nuclear power programmes, especially those that have opted to have their SF reprocessed, using DBD to dispose of small amounts of HLW or SF: the driver would be the possibility of simplifying the concept for the essential national DGR and relaxing the siting and engineering requirements on it, making it easier, quicker and less expensive to design, site, operate and close.
- Countries with no nuclear power but with very small volumes of research reactor SF to dispose of: the driver being similar to that in the previous group – segregating the disposal of SF and simplifying the requirements for geological disposal of reactor decommissioning and operational wastes.

The conclusion thus points to countries or waste management organisations that are looking for a disposal solution for a relatively small inventory. It is in this respect useful to refer to the following quote from IAEA Safety SSG-1 on Borehole disposal of radioactive waste (from 2009, but currently in the process of being updated):

"*An alternative solution is disposal in specially engineered and purpose drilled boreholes (loosely referred to as 'borehole disposal'), which offers the prospect of economic disposal on a small scale while, at the same time, meeting all the safety requirements. The comparative ease of borehole construction and site characterization may make this method of disposal particularly suitable for States, or regional groupings of States, that have limited amounts of waste.*"

This reasoning led African countries in the 1990s to look into the option of borehole disposal at intermediate depth for the disposal of their inventories of disused sealed radioactive sources (DSRS). This initiative has led to the development of the DSRS borehole disposal concept that is planned to be implemented in Malaysia and Ghana. Other countries are also considering this borehole disposal concept for their inventories of DSRS.

Also, countries or organisations managing a large inventory of radioactive waste may take an interest in borehole disposal. This could be because they are looking for a disposal solution for a subset of their inventory. For example, because that subset of radioactive waste does not meet the waste acceptance criteria of the existing or planned disposal solutions and therefore require a dedicated disposal solution. Another reason for such a dedicated solution may be the timing when the disposal route for the large inventory becomes available. This can take many decades. Because of safety, security or economic

[15] Chapman, N. A. (2019). Who might be interested in a deep borehole disposal facility for their radioactive waste? *Energies, 12, 1542; doi:10.3390/en12081542*

considerations, it may be preferred to develop a dedicated disposal solution for a subset of the inventory so that this can be disposed of earlier.

A final example of a scenario where borehole disposal could be interesting for a large inventory, is one where there is a preference to have several different disposal sites. This could be perceived as a way to 'geographically spread the burden' or limit waste transport. One panellist noted that that this is more a theoretical consideration, as large programmes have until now preferred to work on a centralised disposal facility and having several different sites would also require different site characterisation programmes, safety cases and licensing processes.

Finally, one panellist pointed out that, while small-inventory nations may have a stronger incentive for implementing borehole disposal, developing and demonstrating borehole disposal requires resources that large-inventory nations have more of. Ideally, several nations would work together to develop borehole disposal to the point where it was a technology that was available and reliable at the same level as mined repositories (which ideally would also become more standardized and cost efficient).

11 Societal response

Is there evidence to suggest that DBD is likely to be more attractive to communities near a disposal facility, or its isolation and containment capability more readily understood by the public? In this respect, what lessons were learned from the failure to achieve a site for the planned USDOE field test of DBD?

There is perhaps a general view that the simplicity of the DBD concept should make it easily understood and the depth/isolation aspects could make it more attractive than a DGR to the public.

However, the response that a community has to a disposal facility is much more a function of the characteristics of the community, as well as the level of stakeholder engagement. Successful siting is less about the type or design of the facility, and more about the process. For example, it has been shown that communities with a history of nuclear industry activities are more likely to be receptive to a disposal facility - they have experienced and are familiar with the relative rewards and risk perceptions. Similarly, early and continuous public engagement in the siting process enhances the possibility of success.

The proposed USDOE field test in 2016 demonstrated some of these lessons, even though it was a project that did not, and was never planned to, involve the use of nuclear waste or materials.

Initially, the USDOE programme involved a proposed test site in North Dakota and an alternative proposed site in South Dakota; however, the response in the affected communities was sufficiently negative that activities were suspended. These experiences highlighted the importance of public engagement and support for the field test, and that relevant levels of government and other public stakeholders should be involved from the beginning.

Using these lessons learned, USDOE issued a new request for proposals, which emphasized local, state and tribal (if applicable) government engagement, as well as public and other stakeholder involvement, throughout the process. Contract awards were announced for a total of four proposed test sites in Texas, South Dakota and New Mexico, with a final down-select to one site planned, based on contractor team performance and success with local community acceptance.

The stakeholder involvement process was initiated at all four locations, but the project did not proceed to the point of providing lessons-learned, as it was ended before a down-select was made, due to changes in USDOE budget priorities.

12 Expectations

Where are the main technical challenges in building the credibility of DBD to a similar level as DGRs? Where do you think we will be with DBD in ten years' time - is it a solution worth investing in and waiting for?

Borehole disposal is feasible using off-the-shelf technology and methods, but two key areas need to be addressed as a priority: safety concept/safety functions need to be agreed and there need to be field tests of waste package handling technologies. A key technical challenge is to demonstrate the capability for shielded surface handling and downhole emplacement with full size waste containers (without actual waste) and a full-diameter (but not necessarily full depth) borehole. This will demonstrate technical viability and also enhance confidence in the concept.

It is generally agreed that the credibility and appeal of DBD for a wide range of wastes would be increased by raising the perceived limits to the diameter and depth of achievable boreholes. Despite huge advances in deep drilling technology, we do not really know what these limits are, because there has not been a need to find out**.** The perceptions are founded mainly on the requirements and practices of the oil and gas, and geothermal energy industries, plus a few scientific boreholes.

Many of the deep borehole technology subsystems are available and have a high level of maturity, suggested by a panellist to have generally high technical readiness levels (TRL): large-diameter drilling technology (TRL 9), waste emplacement devices (TRL 6), waste immobilisation (TRL 6-9), borehole sealing (TRL 6-9). It was suggested that a full-scale integrated drilling, waste and seal emplacement demonstration project could be completed in less than 10 years and could advance maturity in deep borehole waste emplacement to TRL 7 (cold commissioning with dummy containers). Hot commissioning with real waste canisters would bring the concept to TRL 8, which is the final demonstration step before implementation of the actual disposal system.

Recent work of Panel members involving the UK drilling industry suggests that vertical holes up to over 0.9 m diameter could now be sunk, with existing equipment, to at least 4.5 km, and possibly more, in appropriate geology. This increase in waste capacity, the reduction in the number and cost of holes and an option of increased safety from the EBS (if required) would represent significant enhancements in the potential of DBD beyond current perceptions. Of course, it would still require demonstration, but the cost of drilling a hole to the maximum size and depth possible would only be around £85 M.

With respect to a field demonstration test, one panellist wondered whether a full-scale, stand-alone demonstration facility can be foregone if the necessary tests are carried out successfully with a borehole that is subsequently intended for disposal.

There is, of course, some prior experience of moving towards implementation of borehole disposal, but at shallower depths: the DSRS borehole disposal concept. The concept was proposed in the 1990s and was further developed over almost two decades, including some generic safety assessments. But it was only when Malaysia and Ghana actually kicked off a project to implement the concept, that the concept matured and moved from a conceptual stage to a disposal solution that is close to being implemented. This triggered the interest of many more countries in this disposal solution. This suggests the necessity of a demonstrator or an actual disposal project applying deep borehole disposal to move the concept forward actively.

In ten years' time the drilling industry could be more than ready to implement deep, large diameter boreholes should potential users give a clear, early indication that they intend to pursue DBD as an adjunct to, or an alternative to DGR. The Panel felt that it is not unreasonable to envisage the first operational DBD in about 10 years' time.