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Who Might Be Interested in a Deep Borehole Disposal Facility for Their Radioactive Waste?

Neil A. Chapman

Department of Materials Science and Engineering, University of Sheffield, Mappin St, Sheffield S1 3JD, UK; neil.chapman@bluewin.ch

Received: 27 March 2019; Accepted: 22 April 2019; Published: 24 April 2019

Abstract: The deep borehole disposal (DBD) concept for certain types of radioactive wastes has been discussed for many decades, but has enjoyed limited R&D interest compared to ‘conventional’ geological disposal in an excavated repository at a few hundreds of metres depth. This article explores the circumstances under which a national waste management programme might wish to consider DBD. Starting with an assumption that further R&D will answer technical issues of DBD feasibility, it examines the types of waste that might be routed to borehole disposal and the strategic drivers that might make DBD attractive. The article concludes by identifying the types of national programme that might wish to pursue DBD further and the pre-requisites for them to give it serious consideration.

Keywords: deep borehole disposal; spent nuclear fuel; radioactive waste; waste inventory; geological disposal; repository

1. Introduction

Deep borehole disposal (DBD) involves emplacing solid radioactive wastes at depths of some kilometres in an environment where any groundwater present is likely to be effectively stagnant and unlikely to communicate with the biosphere. Such conditions can result from the density stratification (increasing salinity) of groundwaters and deep fluids at depth and the reduction of topographically driven hydraulic gradients. Such conditions would only be expected at depths of several kilometres, beyond what is technically feasible for a conventional geological repository.

The DBD concept has been around for decades—practically from the inception of projects on geological disposal. For example, a 1976 study [1] looked briefly at (then discarded) ‘super-deep’ (10 to 20 km) borehole disposal and a 1983 study in the USA concluded that the ‘very deep hole concept’ (up to about 6 km) was “credible and the reference system is technically feasible, logical, practical, and achievable by the year 2000, with slight modification of present technology” [2]. The attraction is obvious: compared to conventional geological repositories DBD provides an exceptionally high level of isolation, plus an aura of permanence: containment over tens of millions of years appears achievable. The downside is equally clear: the limited volumes and sizes of waste materials that can be emplaced in a narrow borehole compared to an excavated cavern or tunnel. Layered on top of this are several relevant arguments for and against DBD, principally related to feasibility and economics. If DBD can be implemented successfully, the issue of long-term safety is rarely in dispute.

There is broad international consensus, at practically every level and among most stakeholder groups, that geological disposal (represented by conventional geological disposal facilities: GDFs, constructed at depths of a few hundred metres) is the optimum technical solution for managing long-lived, high-activity wastes (e.g., [3]). On the other hand, the overarching problem for any organisation or nation considering DBD is that there is little consensus on whether this specific form of geological disposal is an appropriate solution, largely owing to a lack of practical experience to rely upon compared to the decades of in situ testing associated with conventional GDFs. The aim of this article is to examine, in the light of this lack of consensus, the circumstances under which DBD might be worthy of consideration as either a major or minor component of a national waste management strategy.

Much has been written about the potential of DBD (e.g., [4–6]), there have been preliminary safety assessments [7,8] and several engineering studies (e.g., [6,9,10]), and proponents argue that the technology, largely derived from the hydrocarbons industry (deep drilling for oil) is already mature and at a high technical readiness level, with only the waste-specific aspects of emplacement to be demonstrated at full scale [6]. Recent tests by a commercial enterprise in the USA have begun to fill that gap [11]. In this article, rather than evaluate all of the previously mentioned arguments for and against DBD feasibility, it is assumed that DBD can be implemented safely and effectively, so is an available option for an agency or country wishing to consider its use. This is a reasonable starting point, given the strong belief among proponents that, with adequate resources, DBD could readily be demonstrated to a level similar to conventional GDFs.

2. What Can Be Put in a DBD Facility?

In this article, DBD is assumed to imply disposal in narrow boreholes (around 300–450 mm completed internal diameter) at depths greater than two to three kilometres (and possibly up to five or six kilometres), with multiple seal systems closing off the upper kilometres of the hole. The top hundred metres or so might be purposely obliterated after sealing, to isolate the waste further and deter intentional intrusion and attempts at retrieval. The geological environment often assumed for the disposal zone of the borehole is crystalline basement rock, but there is no reason that DBD could not be deployed in other, stable, deep geological environments.

What is not considered in the main part of this article is disposal in boreholes or shafts constructed to medium depths of a few hundred metres—the same depth as conventional GDFs. Such boreholes/shafts are more flexible in terms of size and volume, but do not provide the distinguishing feature of DBD—its characteristic high isolation, due to its greater depth. This option is raised again, however, in the conclusions to this article.

The first factor to consider is the types of waste that might sensibly be directed to a DBD facility. Here, there is a fundamental assumption, in common with all geological disposal concepts, that any type of waste under consideration should be solid and sufficiently physically and chemically stable to allow its emplacement in a borehole. We can then examine the technical attributes that would make a waste type suitable or unsuitable for DBD. These are summarised in Table 1 and elaborated below.

Table 1. Technical attributes of wastes with respect to their suitability for Deep Borehole Disposal (DBD).

Technical Attribute	Comments
Attributes making a waste type potentially suitable for DBD	
High concentration of long-lived radionuclides	Would motivate a solution that guarantees a high degree of isolation for a very long period (millions of years)
High specific activity	For example, very high specific activity wastes, even though they contain only short-lived radionuclides
Small total volume	Only a few tens to hundreds of cubic metres: volumes of thousands of cubic metres would require several to many boreholes
Small package size	Maximum diameters of useable borehole space at several kilometres depth are around 400 to 500 mm
Separated fissile material	Nuclear safeguards requirements would motivate guaranteed total isolation with no real prospect of retrieval and misuse
Attributes making a waste type potentially unsuitable for DBD	
Large total volume	Would require many boreholes, which could challenge economics and practicality
Large package size	Would not fit in a borehole: dismantling or reconditioning to smaller packages might be impractical or give rise to operator doses that are unnecessary if an alternative solution exists

Given the size and volumetric constraints, DBD could be regarded as primarily solution for small quantities of high hazard potential and long-lived radioactive materials that are expensive and complicated to deal with. Vitrified high-level waste (vHLW) from reprocessing of used nuclear fuel, along with the spent fuel (SF) itself, are the two candidates most often considered for DBD. Almost all of the six decades of RD&D on geological disposal since the 1950s has been concerned with designing repositories for these heat-emitting wastes.

A deep borehole at, say, 350 mm completed internal diameter, has a capacity of a little under 100 cubic metres per kilometre of disposal length. With the requirements for waste packaging for emplacement, for package handling mountings and for backfill or periodic seals, the actual waste volume will be significantly less. A typical DBD borehole with a disposal zone of a couple of kilometres might thus accommodate of the order of a hundred cubic metres of conditioned waste.

The UK, a nation with a long history of nuclear power and fuel cycle development, has accumulated a large volume of vHLW to dispose of: around 1100 m^3 of material, before packaging for disposal [12]. Countries with medium to small nuclear programmes that have opted for reprocessing possess considerably less HLW: for example, The Netherlands expects to accumulate only 93 m^3 of unpackaged waste by 2130 [13]; Switzerland will have 114 m^3 of vHLW to dispose [14]. Setting aside arguments about vHLW package sizes, which would currently push the limit of feasible DBD diameters, but whose emplacement in deep boreholes is not unfeasible, it can be seen that one or two deep boreholes might be sufficient to take the wastes from smaller nuclear power programmes. In round figures, the UK inventory could require a dozen deep boreholes; the smaller nuclear programmes, one or two.

Spent fuel (SF) exists in much greater amounts than vHLW in most nuclear power nations. Even those countries that have opted for reprocessing might have to dispose of some (or a lot of) spent fuel as well. SF assemblies are slim enough to package for emplacement in deep boreholes with diameters and completions that use available drilling and completion technology. SF is intrinsically less stable than vHLW, in that it contains volatile or readily mobilised radionuclides that could be released if it was damaged during emplacement. This hazard would need to be managed by the DBD package handling technology. Using the same examples as above, Switzerland will have 1357 m^3 of unpackaged SF assemblies to dispose of [14]; The Netherlands has around 100 m^3 of unpackaged research reactor SF, but none from power reactors [13]. The UK already has several thousand cubic metres of unpackaged SF in store, or forecast to arise (and which is unlikely to be reprocessed) and will have considerably more if planned new power plants are constructed and operated. While a small DBD facility for SF thus looks feasible from the volume perspective for the Netherlands, DBD for SF would entail multiple to tens of boreholes for countries with even modest nuclear power programmes.

Consolidation of fuel assemblies has been suggested as a means of making more economical use of borehole volume. This involves disassembly of spent fuel assemblies and closer packing of the fuel rods into disposal packages. It is estimated that this could reduce the required borehole volume (and, hence, number of boreholes) by a factor of three or four, depending on the type of fuel [6]. The specific design would need to show that criticality is not an issue. The additional operation and handling involved in disassembly might not be straightforward, would require special facilities and involve additional operator doses. Also, the fuel assembly components will still require disposal space, as ILW. These additional requirements and impacts are likely to make this approach less attractive than direct disposal of unmodified fuel assemblies, as has already been discussed for conventional GDFs.

Nuclear power plants in the USA are currently storing around 80,000 tonnes (tHM) of SF [15], equal to around 30,000 m^3 of unpackaged fuel assemblies (e.g., a PWR fuel assembly has a volume of about 0.18 m^3 and contains about half a tonne of fuel), potentially requiring hundreds of boreholes, were DBD to be adopted. Some proponents of DBD in the USA have suggested deploying the approach such that each, or localised groups of nuclear power plants (NPPs), have a disposal facility comprising a few boreholes on or close to site.

Small volumes of materials with extremely high specific activity have also been proposed for DBD. In the USA, this approach has been suggested [16] for disposal of separated ^{137}Cs and ^{90}Sr, packaged from the 1960s to the 1980s in about 2000 small (c. 80 mm diameter x 550 mm length) capsules with a total volume of about 6 m^3. This small volume contained about 4×10^{18} Bq of radioactivity in 2006 [17], which will decline by more than half by 2050, owing to the short half-lives of the principal radionuclides in the capsules (although there is a small amount of much longer lived ^{135}Cs present as well). Safety assessments have been carried out to support the DBD disposal concept for these materials [18]. The very high activity of these wastes, combined with their small volume, appears to make them ideal candidates for DBD, but their short half-lives challenges this perspective: after around 1000 years of decay these wastes would be classifiable as low-level waste. Why would they require the geological periods of isolation and containment provided by DBD? At this point, strategic considerations come into play, as discussed in the next section.

DBD has been advanced as an ideal solution for disposal of separated fissile material, in particular from reprocessing of fuel [5]. ^{239}Pu has been separated during commercial (and military) reprocessing for potential re-use in mixed-oxide (MOX) fuel for NPPs, but little has actually been recycled in this way and there are several hundred tonnes in storage, under strict safeguards, in a few countries: the UK, for example, holds, or expects to produce, about 114 tonnes of PuO_2 [12]. Although it constitutes a massive potential source of energy if recycled into fuel, political or technological drivers might eventually dictate that some or all of this material is surplus to requirements and needs to be disposed of permanently. In this case, because it is a fissile material with the potential to be diverted for use in nuclear weapons, a solution that removes it from the human environment into a safe and effectively inaccessible location would be required. The waste form (in particular, the extent to which plutonium would be diluted in the waste matrix) and the packaging in which it would be disposed would need careful consideration with respect to avoiding nuclear criticality, but a few deep boreholes that entomb the material several kilometres down into Earth's crust would have the capacity to manage any national stockpile and would facilitate the demonstration and maintenance of safeguards compared to disposing of the same material in a more accessible GDF.

3. Strategic Considerations in Routing a Waste to DBD

Technical attributes alone are not going to be decisive in whether a particular waste material might be directed to DBD. The technical attributes discussed above dictate whether DBD 'could' be used: strategic and political considerations will dictate whether it 'should' be used. The principal considerations are outlined in Table 2.

An initial comment on the considerations in Table 2 is that some of them overlap, or might need to be considered together. All of the 'suitable' considerations concern timing and/or the availability of alternative disposal routes and can be discussed as a group.

Proponents of DBD assert that a facility could be developed faster than a GDF and operated on a much reduced timescale (e.g., [6]). A GDF requires at least a decade of site investigations at surface and from underground excavations, and development proceeds slowly as new volumes of rock are entered and characterised. Once the access and the underground work areas are constructed, the facility must remain operational until its eventual closure, even if disposal takes place in campaigns. This could be up to a hundred years, in some national programmes. Investigation requirements for rock at several kilometres depth are not as demanding: the DBD safety concept is based on large-scale properties of the geological environment (e.g., presence of a dense, ancient, isolated deep groundwater system) that require less detailed characterisation. A conventional GDF safety case, for example, can depend on detailed understanding of fracture network properties and the ability to pre-qualify each small volume of rock holding a waste package. In addition, constructing a borehole, emplacing waste and sealing it might be achieved within one to two years, after which a DBD facility does not need to remain operational until a further borehole is required: the concept is suited to modular operation in short campaigns.

Table 2. Strategic considerations that point towards or away from DBD solutions.

Strategic Consideration	Comments
Considerations making a waste type potentially suitable for DBD	
No other solution is available	Conventional GDF will not be available for decades, if ever
Time schedule demands	Early disposal of this specific waste material is required: for example, before a GDF becomes available
No other wastes exist in the inventory that require geological disposal	The agency or nation does not have any requirement for a GDF, either because it has no long-lived wastes or it has transferred them to another country for disposal
A site-specific solution is required	The optimum solution for a specific waste is to dispose of it on, or close to, a specific site, rather than being shipped to a central GDF
Remove a problem waste stream	Disposal of a waste that is causing technical problems for storage (and reducing the hazard potential of the national stored inventory) or could be problematic for inclusion in a GDF (e.g., high-burn-up MOX fuel with high and prolonged heat output)
Make a political statement by early disposal	To show that geological disposal can actually be achieved: because we will have to wait years for the main GDF
Economics	DBD for a small amount of waste is less expensive that a full-scale GDF
Considerations making a waste type potentially unsuitable for DBD	
Large volumes of wastes in a national inventory require geological disposal	A GDF will be needed in any case, so why have a separate DBD facility for wastes that could go to the GDF?
Availability of simpler and/or more economic solution	An alternative existing or planned disposal facility meets requirements while providing more spatial flexibility and being less expensive
Requirement for retrievability	Some types of waste are required to remain retrievable for a certain period after disposal in national policy or legislation: this is not practical in a DBD facility

Consequently, if there are strategic or political drivers to get some particular—or *any*—waste underground, DBD offers a potentially attractive solution. It has taken multiple decades to develop GDFs. Even those that have proceeded the most rapidly are into the > 30-year realm. If there is a strategic or political window of opportunity to move forward with geological disposal that needs to be seized, then DBD could demonstrate achievement more speedily than a GDF project, provided that siting (see below) and licensing could be progressed efficiently.

An agency or nation might possess small amounts of waste that could go to DBD and have no requirement for a GDF. This is an unlikely scenario for countries with even modest nuclear power programmes. In addition, almost all nations without NPPs do have some wastes that require geological disposal, so would it apply to any country? Certainly, yes: for example, if a small amount of SF could go to DBD, those other wastes (e.g., from research reactor decommissioning) might be disposed of in a less heavily engineered, less deep, less extensive (in terms of footprint) and less expensive GDF than would otherwise be required were SF also to be accommodated.

A similar situation could arise if a nation were to be in a partnership with other countries to dispose of wastes in a common GDF. The waste acceptance criteria (WAC) for that GDF might preclude it being used for certain wastes for which DBD might then be appropriate. This also seems an unlikely scenario: any common, shared GDF would be expected to have broad enough WAC to accept all wastes from its users, otherwise it does not absolve them from having to develop their own independent facilities as well.

Some types of waste are more difficult to fit into the disposal programme of a conventional GDF and could require either design adaptations or longer operational schedules. For example, the separated Pu wastes discussed in Section 2, if emplaced in a GDF that will remain open to permit long operational periods or to satisfy retrievability requirements, will require design and operational adaptations to meet safeguards requirements. This issue affects few national disposal programmes. A more common problem will arise if there is increasing use of MOX fuel, especially with high burn-ups. Spent MOX fuel emits higher quantities of heat for longer periods than conventional UOX SF and requires either design adaptations in the engineered barrier system of a GDF, protracted operational periods involving programme schedule adaptations, or prolonged storage prior to disposal. Availability of a DBD solution, which is much less sensitive to thermal factors, could become attractive for countries that move to a MOX fuel cycle.

A variety of political and societal reasons might be envisaged why it could be advantageous, or even required, to dispose of wastes at or close to the location where they have been generated or are stored. DBD is intrinsically rather flexible in terms of site suitability: the kilometres-deep geological environment required for DBD is considerably less sensitive to location than the shallow environment requirements for a GDF, where siting is much more critical. Consequently, DBD could be countenanced at many locations. This is one of the reasons that DBD proponents in the USA have suggested numerous NPP-specific disposal facilities. There are some attractions in having the waste generated at a site being disposed at that site and in the area that has benefitted from the presence of the NPP or other nuclear facility. Where there have been obvious disbenefits for the nuclear facility, the argument runs in the opposite direction. For example, residents in the neighbourhood of the Fukushima NPP are strongly opposed to disposing of the NPP wastes on site (e.g., [19]).

For some waste management programmes, an important driver could be the overall economics of disposal. For the scheduling and operational scale reasons discussed above, as well as the limited excavation and engineering involved, DBD is advanced as being a considerably less expensive option than a full-scale GDF. If some of the other factors discussed above also apply (e.g., no GDF will be available for decades), then opting for the less expensive and earlier solution might be attractive. One of the other economic factors that comes into play for a country having both a GDF and a DBD facility is that it could be possible to close the GDF much earlier. The DBD could accept vHLW or SF that is less cooled than would be suitable for a GDF and disposal could be implemented earlier—a GDF that had been used mainly for decommissioning ILW would not then be 'waiting' (possibly for many decades) until SF was ready to be emplaced (see, also, the comments above on MOX fuel). Of course, the discounted costs of protracted storage of wastes until some indefinite time in the future when a GDF does come on-line are arguably small compared to *any* form of geological disposal, including DBD. At this point, other considerations come into play: who is responsible for the costs; what is the policy on intergenerational equity and passing on burdens to future generations etc.

It is clear that the strategic and political factors that might argue in favour of opting for DBD are considerably more complex and potentially constraining than the purely technical attributes discussed earlier.

On the other hand, the considerations that would argue *against* DBD are relatively straightforward. If a nation is already planning a GDF, has a functioning implementation programme to ensure that it will eventually have one and the design concept and WAC are able to accept all relevant wastes in the national inventory, then it could be an easy decision to wait until the GDF is available. Accepting this argument requires trust in the institutions charged with managing the wastes—in particular, their longevity (will they be here to get the job done), the long-term availability of funds to complete the work (the government has not decided to use the funds for something else) and the stability of the national legal and planning framework that permits the GDF over many future decades and changes of government.

Some national policies require that wastes remain retrievable for some period after they are disposed of. The origin of this unusual requirement is entirely societal. In order to progress with public engagement and public approval to proceed with GDF development, a retrievability back-stop has been accepted into policy, in case the GDF does not function to expectations or in case a preferable solution becomes available. There is a distinction between practical retrieval from a GDF and a DBD facility. In a GDF, SF and vHLW are emplaced together with their engineered barrier system and backfills, and are isolated by plugs and seals into disposal tunnels and boreholes. They are in their intended final state with respect to the disposal and safety concept. Sections of the GDF are left open to allow access through plugs and backfill, and make retrievability achievable (if difficult and potentially hazardous). In a DBD facility, retrieval is only possible if the borehole is left unfinished and the wastes are not properly isolated by plugs and seals (although periodic plugs might be essential anyway within the disposal region of the hole). The prospect that heat-emitting wastes containing potentially highly mobile radionuclides (in the case of SF) might be emplaced over a period of a few months, with the borehole, the only realistic route by which activity might be released, then being left unsealed with a key barrier in the disposal system incomplete, perhaps for decades, would seem difficult to justify or license. Retrievability is diametrically counter to the concept of DBD, which aims at the maximum isolation possible by specifically making it practically impossible to retrieve waste once a borehole is sealed and decommissioned. While it has been shown that a package can be emplaced and then, shortly afterwards, removed from a deep borehole using oilfield technology, this demonstration is a far cry indeed from the concept of being able to retrieve all the waste many decades after it has been disposed. Consequently, if retrievability is an immutable part of national policy, DBD is not an option for consideration.

4. The Issue of Siting

As noted previously, a DBD facility should be technically easier to site than a conventional GDF. The isolation and containment concept underpinning DBD is to make use of the undynamic conditions deep into stable regions of Earth's crust, characterised by stagnant, possibly dense, porewaters where the driving forces for fluid movement are extremely small and there is no effective connection with groundwater movement in the more dynamic upper hundreds of metres of rock, where a GDF would be located. In this concept, the details of fracture geometry and connectivity, mineralogy and stress state, which have taxed GDF safety cases and site characterisation programmes, are primarily relevant only insofar as they affect practical issues of borehole drilling and operation. Consequently, in tectonically and geothermally stable regions, many locations could be suitable for a DBD facility. As there are only limited practical constraints on workable depth in the range up to perhaps six kilometres [6,20], then DBD has the added flexibility of being able to go as deep as necessary to find the most appropriate disposal conditions.

Siting, however, is not only a technical issue. As almost every national GDF programme has found out to its cost, in terms of delays and project cancellations, siting is dominated by societal concerns and thus enters the sphere of local and national politics. Even though a DBD provides an apparently higher level of isolation, is much more remote from the surface and has smaller environmental impacts (e.g., spoil, operational period) than a GDF, there is little reason to believe that a DBD facility would be any easier to site than a GDF. In several countries, society is also now sensitised to activities in deep boreholes by the issues surrounding fracking for natural gas production. Siting a centralised national DBD facility using a nationwide screening and volunteering approach—now the common practice for GDF siting—would likely encounter exactly the same problems as siting a GDF.

However, a key aspect of the flexibility of DBD siting is the potential to locate a facility within the boundaries of an existing nuclear site where waste is stored. In principle, and although notoriously unpredictable, the socio-political process of siting and permissioning ought to be more straightforward and less contentious than a 'new', centralised site for a DBD facility or a GDF. This factor again points towards DBD, if and when implemented, likely being a 'boutique' solution—handling small volumes of waste in one or two boreholes, at or close to the site of waste generation. Where this site is a major, historical nuclear legacy facility undergoing extensive remediation, then this approach seems potentially realistic. On the other hand, the model advanced by some proponents in the USA for local disposal of SF at each NPP location, whilst attractive from the viewpoint of logistics, would seem likely to run into exactly the same problems as siting any GDF—multiplied ten-fold across thirty states.

5. Who Might Use a DBD Facility?

Given the discussion above, what type of waste management programme might then consider DBD worth consideration, to meet some or all of its disposal requirements? One way to address this question is by looking at model waste inventories: what types of waste and in what quantities do national programmes need to manage?

Table 3 develops a set of model inventories, with example countries, around which to discuss the question. As the models are generalised, the example national programmes each differs in detail from the broad categorisations, but display most of the features intended. A similar, but not identical, breakdown of waste 'generation cases' has been developed by the IAEA [21] and correspondences between the models and the IAEA case types are noted in Table 3.

Table 3. Model national inventories and the potential relevance of DBD.

Model		Features of the Inventory *	Examples Similar to Model	Comments with Respect to DBD
1	Large NP programme with fuel cycle facilities and legacy (including military) nuclear sites *(included within IAEA Case A)*	SF: 1000–10,000 s m^3 HLW: 1000 s m^3 ILW: 100,000 s m^3	USA, UK, France, Russia	Extensive and complex inventories contain some specific wastes that might be considered for DBD, as well as multiple legacy sites where wastes are stored or being generated during remediation
2	Medium to large NP programme with little or no reprocessing (or mixed fuel cycle policy) *(included within IAEA Case B)*	SF: 1000 s m^3 HLW: 10–100 s m^3 ILW: 10,000 s m^3	Switzerland, Canada, Belgium, Republic of Korea, Finland, Sweden	Likely to be developing a centralised national GDF to contain all higher-activity and long-lived wastes: large amount of SF makes DBD less interesting
3	Medium to large NP programme with reprocessing *(included within IAEA Case A)*	HLW: 100–1000 s m^3 ILW: 10,000 s m^3	Japan, Germany, Netherlands, Italy **	Likely to be developing a centralised national GDF to contain all higher-activity and long-lived wastes: smaller programmes could find DBD interesting for small volumes of HLW
4	Small NP programme with no reprocessing *(included within IAEA Case B)*	SF: 100 s m^3 ILW: 10,000 s m^3	Czech Republic, Slovenia, Mexico, South Africa	DBD potentially interesting if SF volumes are small
5	No NP programme, but research reactor(s) or other nuclear R&D facilities *(IAEA Case C)*	SF: 10 s m^3 ILW: 1000 s m^3	Australia, Denmark, Norway	DBD potentially interesting for small volumes of SF and/or higher activity wastes
6	No NP programme, research reactors or nuclear research facilities *(IAEA Case D)*	Medical, industrial and research (MIR) wastes only	Almost all other countries fall into this category	All wastes would go to near-surface repositories: high specific activity and long-lived disused sources could be routed to borehole disposal at depths of tens or hundreds of metres

* The suffix 's' denotes plural: e.g., 1000 s = thousands. ** Italy no longer has a nuclear power programme: see discussion in main text.

As noted above, in detail, each national programme has its own specific features and waste streams that do not fall rigorously into these generalised models. Germany, for example, although shown as an example of Model 3, also has SF to dispose of because it has cancelled its contracts for reprocessing, and some Model 4 countries possess very small amounts of reprocessed, often experimental, materials.

Countries similar to Models 1 and 2 are managing significant to large amounts of SF. The baseline policy in all such nations is to construct a GDF that would hold the SF, generally alongside any HLW that might exist, plus long-lived ILW that requires geological disposal. The latter can amount to hundreds of thousands of cubic metres, meaning that, regardless of policy towards SF disposal concepts, a GDF will be a necessary part of national strategy.

Would such countries find DBD attractive? Simple logic would suggest that all wastes could most conveniently be dealt with in the unavoidable GDF. However, some of the strategic and political considerations outline in Table 2 could be drivers for directing some element of the national inventory towards DBD. The situation in the USA, where the most recent and most extensive work on DBD has been taking place, shows how major political uncertainties about the GDF programme, combined with the complexities of the waste inventory, can give rise to serious consideration of DBD. As noted above, in the USA, the main call is to consider DBD for localised disposal of SF at or near NPPs, in the continued absence of either centralised storage or disposal facilities. At the same time, R&D has focussed on using a specific category of low-volume, high specific activity wastes to demonstrate the feasibility of DBD.

In summary, while DBD could be of interest to Model 1 nations, countries similar to Model 2 seem unlikely to find it worth serious consideration.

Model 3 nations, with only (or mainly) vHLW to dispose of in the highly-active class, have similar policies to those of Model 2, in that a GDF is a central part of waste management planning. As with Model 2 countries, a GDF will be required in any case for long-lived ILW, which will arise from decommissioning and, unless it has been retained and substituted for extra vHLW by the reprocessor, from fuel element debris from reprocessing. Unlike Model 2 countries, the vHLW will be generated centrally at a reprocessing plant, or stored centrally, if reprocessing took place abroad. This indicates that a centralised disposal concept will also be part of national policy. Large programmes have considerable volumes of vHLW to dispose of (e.g., the example of Japan, which will have to dispose of 40,000 vHLW containers—about 6000 m^3), meaning that a centralised DBD facility would require many boreholes. However for those nations with relatively little vHLW to dispose of, then some of the strategic arguments on scheduling and demonstration of progress in Table 2 might make DBD a consideration for vHLW. This could be especially interesting if it means that the requirements on a GDF (now containing no vHLW) become less stringent, allowing, for example, a shallower or less engineered facility to be built for ILW.

As a hypothetical example, the DBD requirements for a country with two NPPs operating for 60 years and wishing to dispose of all the vHLW produced over the lifetime of these plants (about 300 to 500 m^3) would be about 3–5 km of disposal length: say, two to three deep boreholes with disposal zones between 1 and 2 km long. Italy provides an interesting example of Model 3. It had extensive nuclear research facilities and a medium-sized nuclear power programme until 1987, when it was decided to withdraw from nuclear power generation. Almost all the SF produced has been, or is to be, reprocessed abroad, with the resulting c.90 m^3 of vHLW returned to Italy, to a planned centralised storage facility, where it will be kept with an eventual 13,700 m^3 of ILW [22].

In summary, there could be worthwhile arguments for a Model 3 small NP programme that reprocesses its SF to consider segregating its vHLW for DBD, with only a few boreholes being required.

Countries similar to Model 4 would have small volumes of SF to dispose of and might consider emplacing these in a DBD facility for the same reasons as Model 2 nations with smaller nuclear power programmes: it could make the necessary (for ILW) GDF considerably less demanding to develop and operate. In addition—and a major argument for Model 4 nations that have SF—DBD is considered to be considerably less expensive than GDF disposal, for small SF volumes. However, the disposal volume required for SF is greater than for vHLW, so more boreholes would be required than for a Model 3 nation with a small nuclear power programme. For example, disposing of slim packages each containing a single PWR fuel assembly (around four to five m long and containing about half a tonne of fuel) would require a borehole length of about 10 metres/tonne SF. Using the same 2-NPP model discussed above for Model 3, the lifetime disposal requirements for a 2-NPP nation (around 3000 tHM of SF) would amount to about 30 km of disposal length (say, 15 to 20 boreholes), ten times greater than in Model 3 (or less, if fuel rod consolidation were to be considered). Nevertheless, for a country with only one NPP, DBD might prove attractive, especially if it were to move towards the use of MOX fuel.

Model 5 covers countries with no nuclear power programme, but with research reactor facilities. Many countries falling into this category have had arrangements to repatriate the fuel (usually high-enriched fuel) from their research reactors to its original supplier nation and thus might be considered to have no interest in DBD for their SF, being more similar to nations falling into Model 6. However, several countries (e.g., Denmark, Norway) already have to manage their own, historic research reactor and/or experimental fuels, and this will increasingly be the case with the switchover from high-enriched to low-enriched fuel in almost all countries. In all cases, some type of GDF needs to be considered, for disposal of reactor decommissioning wastes, but a similar argument applies as for Models 4 and 5: the GDF requirements could be relaxed if no SF were to be included.

The lifetime volumes of spent fuel from a research reactor are low. Packaged for disposal they would amount to a few, to a few tens, of cubic metres, making DBD a potentially attractive option to consider. Some countries are considering reprocessing the small amounts of SF they hold, which would make the disposal volume requirements even smaller. Countries with advanced nuclear research facilities are likely also to possess small volumes of other high activity materials that might be considered for DBD.

There are no requirements for DBD in countries with no nuclear power and no nuclear research reactors or related facilities: Model 6. Although all countries generate radioactive wastes, the low activity of almost all the material is suitable for near-surface disposal, often as exempt materials. The exceptions are high specific activity sealed radiation sources used in medicine, industry and research (MIR waste). Disused or spent sources that are not returned to their manufacturers or cannot be managed by decay storage can be considered for borehole disposal at tens or hundreds of metres depth. This solution has been extensively studied over the last 20 years [23], and borehole disposal projects for disused sources are on-going in Ghana and Malaysia today. While the highest activity and longest-lived disused sources could be routed to DBD if it were being developed for other wastes (e.g., in Model 5 countries), the level of containment and isolation provided is not justified for Model 6 countries when disposal in boreholes at conventional geological disposal depths would be adequate.

6. Conclusions

In terms of depths and diameters, there is a continuum of borehole-type disposal facilities that are available for small inventories of waste of different categories, but there are few examples of operational facilities worldwide. The disposal options available to nations with small inventories are under review at present by the IAEA [24], with boreholes and shafts being part of the spectrum of feasible solutions. Both narrow boreholes (< 0.5 m internal diameter) and shaft-type repositories (ca. five to 20 m in diameter) constructed to depths from several tens to around a hundred metres are potentially suitable for many categories of longer-lived ILW. The narrowest (boreholes) are suitable for small items such as disused or spent sources; the widest (shafts) can be used for larger packages and some large, un-dismantled reactor components.

DBD then takes a major leap to considerably greater depth—up to several kilometres—with the possibility of disposing of packages up to almost 500 mm in diameter in prospect. As discussed in this article, DBD is a solution reserved for high activity materials, particularly those that are long-lived and/or of a fissile nature. The question raised in the title to this article is "who might consider a DBD facility?" This article has assumed that the key safety and engineering aspects of DBD can be successfully demonstrated and audited in the near future such that feasibility is not challenged. From this starting point, the arguments presented in this article indicate 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.

To answer the question posed, the discussion of Model inventories in the previous section can be summarised as suggesting that only the following types of user country might be likely to give DBD serious consideration—possibly for the reasons stated below:

- *Group A*: Countries with major historic nuclear development, extensive fuel cycle facilities and complex waste inventories (Model 1): the major drivers might be lack of progress with a GDF 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.
- *Group B*: Countries with small nuclear power programmes, especially those that have opted to have their SF reprocessed (Models 3 and 4), using DBD to dispose of small amounts of vHLW or SF: the driver would be the possibility of simplifying the concept for the essential national GDF

and relaxing the siting and engineering requirements on it, making it easier, quicker and less expensive to design, site, operate and close.

- *Group C***:** Countries with no nuclear power but with very small volumes of research reactor SF to dispose of (Model 5): the driver being similar to that in Group B—segregating the disposal of SF and simplifying the requirements for geological disposal of reactor decommissioning and operational wastes.

The stage between 100 m deep boreholes and DBD—the use of boreholes to typical GDF depths of 500 m or so—was mentioned at the beginning of this article. It has not so far been exploited for solid radioactive waste disposal in any country. Given the right geological environment for a disposal site, it could provide a better alternative to DBD for the Group C users defined above, in that it is less expensive and could be less technologically demanding. However, it provides less isolation and it is less easy to make a safety case for containment than for a DBD for the same wastes, requiring equivalent levels of site characterisation and safety case development to those for a GDF. Choosing between this, medium-depth borehole option and DBD will thus need a thorough evaluation and balancing of user requirements.

7. A Look to the Future

While the safety concept and the facility requirements (especially operational) for a DBD are simpler than those for a conventional GDF, there is a need now for practical testing of deeper borehole disposal, whether it be the c.500 m concept mentioned above, or DBD itself. Deeper borehole disposal has not enjoyed the decades of development that have been devoted to GDFs.

To catch up and move forward, there seem to be several pre-requisites for any country to give serious consideration to the use of DBD:

- It must be demonstrably practicable: this point is getting closer with current trials of some aspects in the USA [11] but there is some distance still to go, particularly with respect to SF disposal;
- Increased flexibility with respect to package dimensions: the ability to construct wider boreholes at disposal depth would have direct impacts on the numbers of holes required for a given inventory, on the ability to emplace existing vHLW and associated ILW containers, and thus on economics—such advances in technology would seem reasonable to expect in future;
- There is a need for several iterations of generic operational and post-closure safety cases: at present there are very few examples and they are not as comprehensive (e.g., In terms of the scenarios assessed) as their numerous counterparts for GDFs;
- Positive signals from regulators that they could be satisfied by a DBD a safety case: we know this can be done for a GDF (e.g., Finland) and if there were DBD precedents it would be easier to bring it into a national waste management schedule early on;
- No national/legal concern about retrieval: this simply requires a sensible policy decision tailored for DBD, rather than applying policy that was designed to satisfy progress on conventional GDFs;
- More comprehensive economic analysis to show that DBD cost will be the same or less than the marginal/variable costs of expanding a GDF to take the same wastes;
- A requirements-led system engineering approach to national waste management planning inclusion would help to decide whether inclusion of DBD in policy would optimise overall waste management strategy.

The potential for using deeper boreholes to manage small inventories of waste is high. As discussed in this article, however, rather few countries are likely to consider using the high isolation provided by DBD and then only for a limited range of materials. In the *Group A* nations, this situation will only change if strategic requirements evolve (effectively meaning that continued, protracted storage, coupled with lack of a credible GDF programme, becomes a political problem) and when DBD has been more extensively demonstrated. In most cases, these country's national GDF projects (which will be needed anyway) are going to take decades, so they might consider that they can afford to wait and see, then fit in DBD, if required, at an appropriate time.

Perhaps the most likely developments will be in some *Group B* or, especially, some *Group C* countries, where the drivers for DBD are strongest, the volumes of waste are small and manageable, the problems are centralised and the resources are available to trial the technologies involved.

Funding: This article received no external funding.

Acknowledgments: The author wishes to thank Philippe Van Marcke and Karl Travis, plus three anonymous reviewers, for their valuable comments on an initial draft, which have significantly improved this article.

Conflicts of Interest: The author declares no conflict of interest.

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