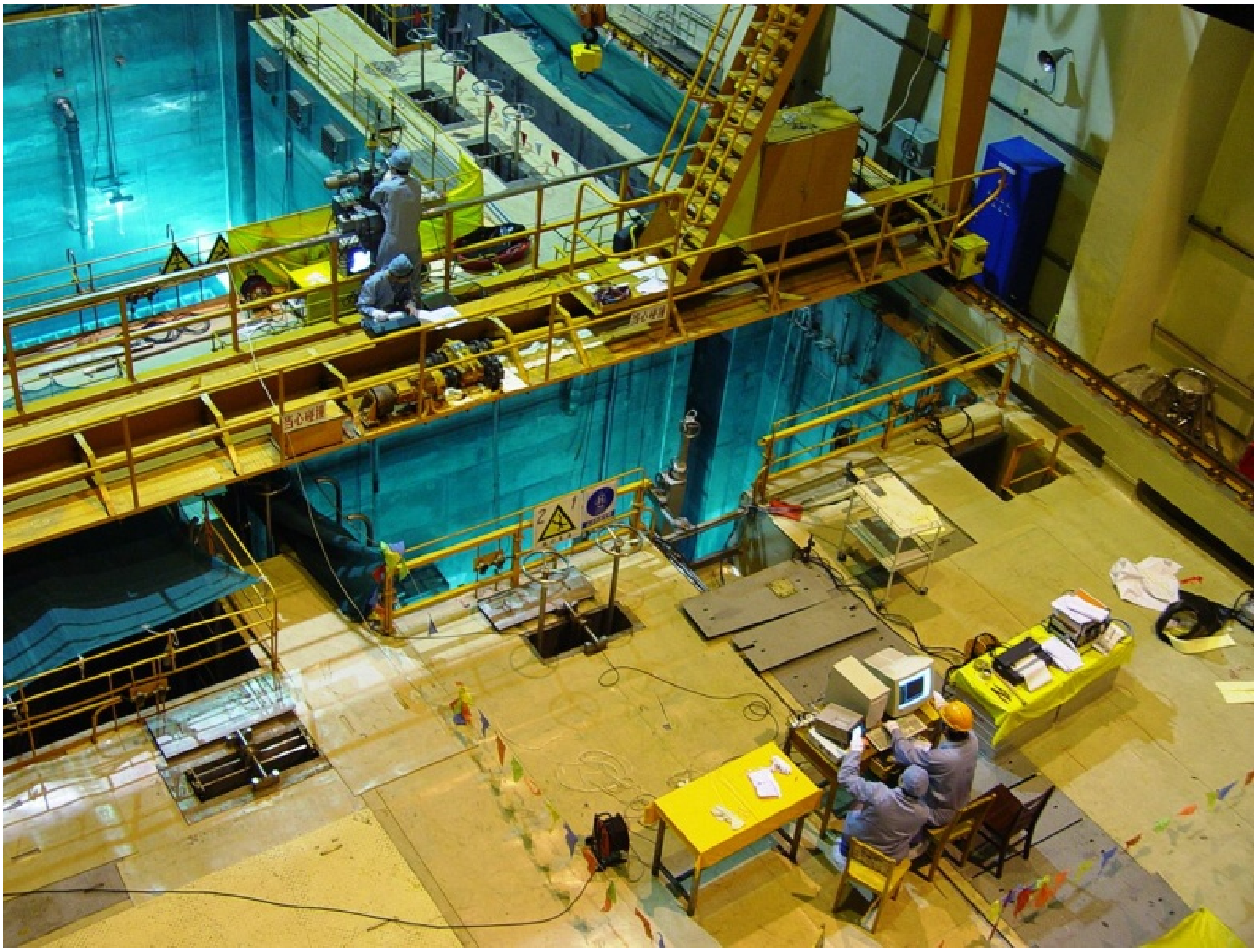
Deep Borehole Disposal of Spent Fuel: International Developments and Implications for NE Asia



Recommended Citation

Neil Chapman, "Deep Borehole Disposal of Spent Fuel: International Developments and Implications for NE Asia", NAPSNet Special Reports, March 24, 2014, https://nautilus.org/napsnet/napsnet-special-reports/deep-borehole-disposal-of-spent-fuel-international-developments-and-impli-ations-for-ne-asia/

by Neil A. Chapman

25 March 2014

This Special Report was originally published as a Working Paper 2013-12 by the Center for Energy, Governance and Security at Hanyang University, Seoul.

I. INTRODUCTION

Deep borehole disposal (DBD) has been discussed as a possible means of disposing of spent fuel (SF) from nuclear power reactors in some East Asian countries, to support a prospective nuclear weapons free zone in the region, and to help to avoid security and sustainability dilemmas associated with the management of rapidly growing quantities of SF. This Working Paper examines the status of the DBD concept and discusses some of the implications for SF strategy in East Asia, with special emphasis on NE Asian countries.

The concept of deep borehole disposal (DBD) of spent fuel, high-level nuclear wastes (HLW, generated during the reprocessing of spent fuel to extract plutonium and uranium) and other radioactive wastes has been discussed actively for many decades. The US Nuclear Waste Technical Review Board identified DBD as a "technically viable type of geologic disposal". In fact, it is a significant variant of 'conventional' geological disposal in deep underground repositories, which are mined facilities that can be accessed by shafts and tunnels during operation, and which have extensive underground cavern and tunnel excavations. Nevertheless, DBD retains many conceptual similarities with conventional repositories in terms of the way in which long-term containment and isolation of radioactivity are provided.

DBD involves emplacement of waste packages in the bottom sections of boreholes constructed to depths of several kilometres, with the upper kilometres of the holes not used for disposal, but backfilled and sealed, possibly with the uppermost sections being obliterated to make relocation difficult and re-access problematic. Typically, waste might be emplaced in sections of a borehole at depths from 3 to 5 km, with the safety concept being based principally on the considerable isolation provided by the great depth.

In principle, DBD can be seen to be an essentially irreversible option – or, at least, an option where retrieval of wastes could be made extremely difficult. For this reason, it has been suggested as an especially appropriate solution for disposal of fissile materials such as separated plutonium (Pu), where nuclear safeguards will be of central concern. As the volume of a deep borehole is restricted, DBD is not seen as a solution for large volume waste streams (most intermediate level waste – ILW – streams, for example). Consequently, all work has concentrated on the use of DBD for disposal of HLW and SF (plus conditioned Pu waste forms: typically, ceramic or glass, containing relatively small concentrations of Pu).

The most comprehensive recent evaluations of DBD have taken place in the USA. A review was carried out by the Massachusetts Institute of Technology[1], an extensive study was made by Sandia National Laboratories (SNL)[2] and a recent evaluation was prepared by von Hippel and Hayes of the Nautilus Institute[3]. The drivers for the SNL and MIT reviews resulted from the demise of the Yucca Mountain Project in 2009. Yucca Mountain was to be the geological repository for much of the SF and HLW coming from US reactors, but it has been abandoned, owing to a combination of technical and political issues, following expenditures of tens of billions of dollars. The 'Blue Ribbon Commission' (BRC) appointed by President Obama subsequently looked at ways forward for SF and radioactive waste management, including DBD alternatives to SF disposal in conventional geological repositories.

DBD studies have developed very slowly in other countries, although interest has remained active. In 2006, Åhäll reviewed[4] the state of knowledge for MKG, a Swedish NGO (their interest being in DBD as an alternative to SKB's plans for disposal of Sweden's inventory of SF in a conventional geological repository). Åhäll observed that DBD might offer important advantages compared to conventional geological disposal, in that it has the potential of being more robust:

"The reason for this is that very deep borehole disposal appears to permit emplacement of the waste at depths where the entire repository zone would be surrounded by stable, density-stratified groundwater having no contact with the surface, whereas a KBS-3 repository would be surrounded by upwardly mobile groundwater.

This hydrogeological difference is a major safety factor, which is particularly apparent in all scenarios that envisage leakage of radioactive substances. Another advantage of a repository at a depth of 3 to 5 km is that it is less vulnerable to impacts from expected events (e.g., changes in groundwater conditions during future ice ages) as well as undesired events (e.g. such as terrorist actions, technical malfunction and major local earthquakes). Decisive for the feasibility of a repository based on the very deep borehole concept is, however, the ability to emplace the waste without failures. In order to achieve this further research and technological development is required".

In the UK, there is a continuing programme of research work at the University of Sheffield, focussed on thermal modelling of a variety of DBD concepts, where the heat emitted by the waste is used to develop seals of various natures in the disposal zone. In 2007, the UK Nuclear Decommissioning Authority (NDA) commissioned a study[5] of deep borehole construction technology to consider the feasibility of drilling large diameter holes to great depth and of carrying out operations in such holes.

A key gap continues to be a comprehensive operational and post-closure safety assessment of DBD. It is also recognised that the lack of full-scale trials of certain aspects of the technology (not necessarily at envisaged disposal depths) is holding up further development.

II. SPECIAL REPORT BY Neil A. Chapman: 1. DBD Concepts and Technologies

Arnold and co-workers[1] and Gibb[2] have outlined the various methods currently under consideration for DBD. Gibb and co-workers at the University of Sheffield in the UK describe a current classification of low and high temperature disposal concepts:

- in **low temperature concepts,** the heat emitted by the SF or HLW is conducted away through the near-field rock without causing any significant changes in the properties of natural barrier, although being sufficient in some concepts to cause melting of a dense backfill matrix, which then re-solidifies to form part of the engineered borehole system;

- in **high temperature concepts** the heat emitted by the wastes is much greater and is utilised to cause melting of the rock which, upon cooling and solidification, contributes to the containment of the wastes.

In high temperature concepts, HLW or SF is disposed of earlier than in conventional geological disposal (GD) concepts, whilst its heat output is greater. Whilst the DBD concept began its life principally as a high temperature, rock-melting and solidification model, the present consensus among proponents of DBD appears to be more interested in passive, low temperature solutions, as it is not possible to monitor or control active rock melting processes to the extent that is likely to be required in developing a safety case. Figure 1 illustrates the three concepts defined by Gibb (two low temperature concepts and one high temperature concept).

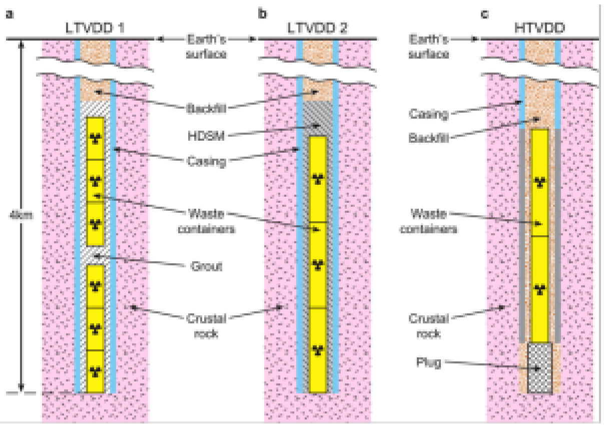


Figure 1: Schematic illustrations of the two low temperature (left and centre) and one high temperature (right) concepts defined by Gibb and described in the text. The HTVDD concept is being less actively considered internationally than the low temperature concepts.

Gibb proposes that, in the first low temperature concept (LTVDD 1: low temperature very deep disposal 1), a special, highly fluid, high-temperature cement similar to those used in geothermal energy wells would be pumped down the hole to fill the space between the packages and the borehole casing, and any gaps between the casing and the wall rock, with package emplacement taking place in campaigns, allowing setting of the backfill. Heat flow modelling[3] indicates that temperatures in the borehole adjacent to the waste packages and in the wall rock will peak at 100° to 200°C above an ambient temperature of between 60° and 140°C at between one and three years after emplacement. This approach is advanced principally for vitrified HLW disposal, but could also be used for ceramic or other Pu-containing wasteforms.[4]

In Gibb's model for SF disposal (LTVDD 2: low temperature very deep disposal 2), fuel pins from disassembled fuel assemblies would be placed inside stainless steel containers which would be heated slowly to c.335 ºC in an inert atmosphere to prevent oxidation of the cladding, with molten lead filler being poured into the voids in the container, which would then be sealed. Containers would be deployed in fully-cased boreholes (boreholes lined with steel piping), and a special high-density support matrix (HDSM) would be used to eliminate the possibility of damage from load stresses imposed by the overlying stack. Gibb and co-workers[5] have developed the concept of a HDSM composed of fine lead-alloy shot, released into the borehole above the topmost container, partially to displace the aqueous borehole emplacement fluid and fill the annulus between the containers and casing. Heat from the spent fuel will generate temperatures 100-200ºC above ambient and melt the shot to create a dense liquid that will displace the aqueous fluid upwards and fill any remaining voids between the containers and wall rock. Within a few decades, the HDSM will solidify.

Current studies at the University of Sheffield are also evaluating the practicalities of producing a seal above the disposal zone in a low-temperature disposal version, by inserting a heater in a section of the borehole from which the casing has been removed and melting the rock over a distance of a few metres. On cooling and recrystallization, a seal is formed that is continuous with the host rock. The intention is to provide effective isolation and containment by closing any possible migration pathways up the borehole or in the drilling damaged zone that lies in the rock immediately adjacent to the borehole walls.

1.1 Recent work in the USA

In the last few years, collaborative work has been performed by Sandia National Laboratories (SNL) and the Department of Nuclear Science and Engineering of the Massachusetts Institute of Technology (MIT) in the USA. An international review workshop in 2010 was the first time DBD proponents had come together to identify issues and R&D needs if DBD were to be considered seriously for deployment.

The MIT group has issued a number of progress reports describing their R&D programme[6] and the results of the 2010 workshop were outlined by Brady and Driscoll[7]. Prior to this, a 2009 report by SNL, reported the results of the first performance assessment that has been carried out for DBD, using techniques common to those used for conventional geological disposal. The report was concerned with disposal of the US inventory of SF. It concluded that all used fuel from the existing US LWR reactors could be emplaced in approximately 1000 deep boreholes (109,300 tHM of SF and HLW could be disposed of in ~950 boreholes) with a total cost that is competitive with mined repositories (roughly 70 billion USD).

SNL also concluded that long-term performance is likely to be excellent, with estimated peak doses from a single disposal borehole containing 400 PWR assemblies of 10^{-12} mSv/a. The report states:

"Significant fluid flow through basement rock is prevented, in part, by low permeabilities, poorly connected transport pathways, and overburden self-sealing. Deep fluids also resist vertical movement because they are density stratified. Thermal hydrologic calculations estimate the thermal pulse from emplaced waste to be small (less than 20 C at 10 meters from the borehole, for less than a few hundred years), and to result in maximum total vertical fluid movement of ~100 m. Reducing conditions will sharply limit solubilities of most dose-critical radionuclides at depth, and high ionic strengths of deep fluids will prevent colloidal transport".

Whilst this study was the first to attempt a quantitative performance assessment of DBD, it was much simplified and conservative. The radionuclide release scenarios addressed were two 'up the hole' pathway analyses (requiring failure of borehole seals or a continuous, high permeability damaged zone along the borehole wall) and one involving lateral movement from the disposal region of the borehole, through fractures in the host rock. Criticality scenarios (scenarios in which fissile nuclear materials placed in the borehole became concentrated enough to sustain a nuclear reaction) were omitted as they were considered to be of very low probability or not credible. The PA study focussed on the up-hole scenarios, with releases being driven by thermal convection up a poorly sealed borehole into a region where water is abstracted by a well. The only radionuclide to give rise to doses was ^{129}I, with doses at extremely low levels (see above).

SNL concluded that further work is needed to test preliminary observations about long-term performance. Further important conclusions of the study were that:

- detailed cost analysis would be beneficial;

- consideration of changes in legal and regulatory requirements will be needed;
- detailed analyses of engineering systems and operational practices for emplacement are needed;
- a full-scale pilot project should be undertaken.

Work at MIT has covered a range of prospective applications of DBD and initially focused on 40 to 50 cm diameter holes drilled into crystalline granitic bedrock using available oil/gas/geothermal industry technology. The holes are fully lined using grouted in-place standard steel drill-pipe, with a maximum depth of 3 km, and a 1 km waste emplacement zone. The MIT group suggests the use of graphite “sand” as a lubricating/thermally conducting infill between the waste canister string and borehole wall liner, to increase the prospects for retrievability. The somewhat shallower depths now being considered (3 km, instead of 5 km), result in lower bottom-hole lithostatic and hydrostatic pressures. A 1000 m emplacement zone is estimated to result in canister stack weights that will not crush the bottom-most canisters, with a significant factor of safety.

At a 2010 SNL-MIT workshop, discussion focussed on four main areas: borehole operations, retrievability, site characterisation and licensing. It should be noted that this workshop was concerned mainly with the disposal of SF and with the US siting and licensing situation, so the conclusions are not necessarily transferrable elsewhere. Among the perceived favourable characteristics of DBD, the MIT group identified that the concept is inherently modular (drill as required – ‘pay as you go’), there is widespread applicability and thus the possibility of sharing international R&D, a simpler safety case can be made, and there is the possibility of separately licensing the borehole technology and the disposal facility (analogous to generic reactor design licensing), thus potentially facilitating the process of obtaining requlatory approval for DBD installations.

The perceived disadvantages of DBD included two that are often cited: the difficulty of managing large diameter boreholes (c. 0.5 m) and the difficulty of retrieving waste – although this could also be an advantage when considering nuclear safeguards. The key MIT findings over the 20 years during which they have considered DBD were stated to be that the prospects for very effective sequestration of radioactive wastes are high, the concept is cost-effective, and the two main concerns in safety evaluation are the mobility of ^{129}I in SF and the quality of the borehole seal.

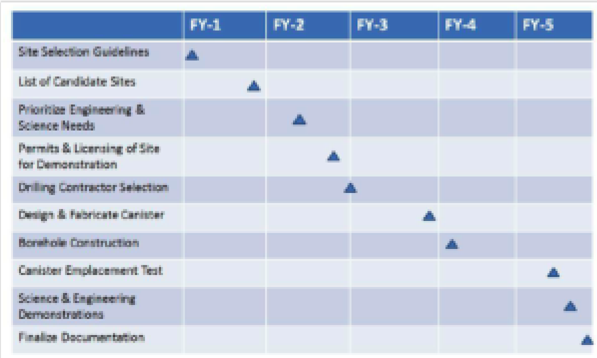
Discussions on borehole operations focused on the need to understand drilling damage (extent and properties of the disturbed zone close to the borehole) and on the need for high integrity, low permeability seals to assure long-term isolation. Potential operational problems during emplacement, including damage to canisters and waste during the trip down the borehole, should be minimized, and it may be desirable to line the hole for its entire length with steel casing.

A list of R&D questions was generated and prioritised, including the design of Pilot Tests at shallow depth, for testing emplacement engineering, and at full depth. In this respect, the conclusions of the 2009 Sandia report that preceded the workshop note:

“It is recommended that ultimately a full-scale pilot project be undertaken, perhaps with surrogate waste, in order to fully explore the viability of a borehole disposal concept. The scientific and engineering advances gained from a single pilot project, and the applicability to subsequent borehole disposal implementations, are in contrast to site-specific mined repositories and their unique site characterization demands with relatively little transferable knowledge to subsequent repositories. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards,

and accelerate the evaluation of the viability of deep borehole disposal of spent nuclear fuel and high-level radioactive waste."

Regular workshops have followed the initial 2010 meeting, and Sandia has recently (2012) prepared proposals for such pilot studies as part of the US programme. The outline plan is presented in the form of a road-map for DBD research[8], whose proposed schedule is shown below:



1.2 Developments in the UK

Independently of the SNL developments, Gibb has proposed an outline approach for large-scale testing of DBD technology in a UK context[9], using a full sized (0.5 m inner diameter) cased borehole, initially constructed to a depth of only a few hundred metres, with its bottom end made accessible from pre-existing tunnels or mine workings, to enable examination. Repeated emplacement and recovery of dummy packages could test various methods and equipment, the reliability of package deployment and the ability to recover packages in the event of a problem. The emplacement of materials to fill and seal the spaces around the waste packages and gaps between the casing and wall rock could be simulated using waste packages containing an electric heater. The emplacement, melting and solidifying of a HDSM could also be tested. An important demonstration would be the cutting of un-cemented casing above the deployment zone, its recovery and the effective sealing of the borehole. A further step would then be the testing and demonstration of aspects of borehole and package handling technology at full DBD depth.

Parallel developments for disposal of HLW or SF waste containers in long vertical boreholes in salt may offer the potential for technology transfer to DBD. The German concept for HLW and SF disposal in dome salt formations is based upon c.300 m long boreholes constructed from tunnels in a conventional geological disposal facility (GDF). DBE Technology[10] has carried out full scale testing of handling technologies for package emplacement that has overlapping technical elements with the borehole-top technologies that would be required for DBD.

Discussion of the DBD concept and its identification by a UK government advisory committee (CoRWM) as something that needed to be kept under review led to an evaluation of the deep, relatively large diameter borehole technology that would be needed for DBD by Beswick[5]. Subsequently, Beswick made an updated presentation of DBD technology issues[11], in which it is concluded that a 500 mm to 600 mm diameter borehole to a depth of 5000 m in crystalline rock is not far outside the current experience envelope of the drilling industry and is achievable with tool and process development. Appropriate drilling rigs are available and drilling systems can now assure verticality. Casing through the full length of the borehole would be essential. Beswick considers that the time for drilling, waste emplacement and completion of a single 600 mm diameter DBD borehole could be as little as three years, in contrast to the decades that are typically considered required to construct and operate a mined geological repository.

A pilot scheme for developing processes, systems and tools is considered to be relatively inexpensive, with casing-cement-rock integrity issues and sealing and needing special attention. Beswick also acknowledges that deep borehole disposal will probably be cheaper (than conventional geological disposal), for the wastes that can be accommodated, citing a cost of 35 to 40 million GBP for construction of the first boreholes, with cost declining significantly with subsequent holes. MIT suggests that developments in drilling techniques in coming years (including projectile drilling, spallation drilling, laser drilling, and chemical drilling, none of which is commercially available at present) could significantly reduce costs.

2. Possible applications in national GD programmes

The US national programme on DBD is currently considering pilot tests and demonstrations of aspects of the technology. In this case, it would seem likely that other topics from the list of R&D requirements outlined previously would also be addressed. The thrust of the concept being considered in the USA is that multiple DBD facilities could dispose of SF, possibly at NPP sites.

In Sweden, DBD has been evaluated at a low level of activity for many years, as a possible alternative to conventional GD for SF. There is a requirement for SKB to consider and report on alternatives in its license application for disposal. Given the interest in DBD from Swedish NGOs, the concept will likely be discussed actively over the next two years, as part of the current licensing and approvals process for the mined repository for SF in Sweden.

DBD is being proposed by the Nautilus Institute as a possible solution for SF management in Northeast and East Asia, with a major emphasis on the non-proliferation advantages of the concept[3]. SF inventories in the region are growing rapidly, and the Nautilus report asserts that the DBD approach would avoid many of the proliferation-prone steps involved with reprocessing and recycling fissile material from SF, as well as possibly proving more acceptable socially and politically, more economic in the short and long run, and less hazardous with respect to the technological and ecological risks arising from the disposition of large amounts of radioactive material. Possible institutional configurations for DBD in East Asia are suggested to include the use of the technology by each nation going it alone, by some nations contracting for disposal with a few service supplying nations, or through the coordinated development and operation of one or a few central deep borehole facilities used and governed by all of the key nuclear user (present and future) nations of the region. The study concludes by proposing a multi-disciplinary collaborative programme of research designed to evaluate, systematically and comprehensively, the relative attributes of the technical, cost, security, safeguards, and other benefits of different nuclear fuel cycle management approaches, including DBD, with a view to determining which of these approaches best supports a prospective nuclear weapon free zone in East Asia.

3. Some Technical Implications of Incorporating DBD in a Conventional GD Programme

The continued interest and potential for further developments in DBD means that this alternative to conventional GD for some categories of waste may become a more feasible candidate for consideration as a part of any national GD programme. If this were the case, then DBD might be considered alongside conventional GDFs, as most national programmes would still need the latter (e.g. for some ILW), even were DBD available for some of their wastes.

The size of a conventional GDF is heavily influenced by the tunnel lengths required for disposal of HLW and SF containers, so shifting some wastes to DBD could affect GDF footprint and costs considerably. Redirection of certain categories of waste to DBD would also affect requirements for the repository surface facilities (there would be different requirements for packaging of SF to those used in a repository) and repository access arrangements. There are parallel cost implications. As no scenario would envisage all categories of high-activity and long-lived wastes being directed to DBD, the cost of a DBD becomes additional or marginal to that of a conventional repository, depending on the inventory under consideration.

The use of DBD also has implications for repository siting. Many nations consider it preferable to have all waste disposal concentrated in one siting area, so locations would need either to be suitable for both DBD and conventional repository construction, or a separate but nearby site in a repository siting region would be required for DBD. Site characterisation work would need to be extended to fit the requirements for characterising the very deep geological environment. These requirements have not yet been considered in detail, as they are closely related to DBD safety case development, which has only just begun. Alternatively, as in the USA, the concept of having several local DBD facilities (even one for each NPP complex) means that DBD sites might be developed in multiple locations. The considerable depth makes the concept less sensitive to geological conditions than a conventional GDF, so multiple sites appear, at face value, more feasible.

The time-scheduling implications for a disposal programme also need to be considered. In principle, DBD is amenable to deployment in short 'campaigns', which could be linked to the requirements of a particular NPP siting region. Wastes could be stored (for example, in at- or near-surface storage facilities, including facilities using "dry casks"—massive steel and concrete containers that can store spent fuel for many decades) for protracted periods until a campaign was required to empty storage facilities. As wastes may not need to be stored for prolonged cooling before disposal, it is clear that there are many permutations of storage and disposal timing that could fit a national strategy.

4. Consideration of DBD in three NE Asian countries

At a May 2013 meeting in Beijing, organised by the Nautilus Institute, current considerations of the potential for DBD in a number of NE Asian countries were discussed.

In China, deep borehole disposal is not currently considered as an option for HLW management, and has not been studied closely. China has a reprocessing policy for spent fuel and the resulting high-level waste will likely be disposed next to the reprocessing site. An agreement is being pursued with France for the development of a large-scale reprocessing plant. Commercial drilling capabilities in China currently extend to 4 km deep holes and mainly focus on mining exploration. In 2005, China's national drilling R&D project completed a 5 km deep borehole. At present there is an incomplete regulatory system to regulate all nuclear activities, including nuclear waste management, disposal and a possible spent fuel disposal fund. Radioactive waste R&D has so far not attracted a high funding priority. Chinese colleagues reported that future developments of the DBD concept in China would be enhanced and facilitated by increased international co-operation.

In Japan, although the Nuclear Waste Management Organization (NUMO) identified DBD as an option in 2004, there has been little interest in the approach and no work has been carried out. Japan has several very deep holes, constructed by the Ministry of Economy, Trade and Industry in the 1990s to depths greater than 6 km, with bottom diameters up to 24 cm. The stability of deep (especially geothermal) boreholes has been an issue, with casing collapse problems reported. In addition, certain areas of Japan are characterised by upwelling deep crustal fluids and may be unsuitable for DBD. For the 40,000 HLW vitrified HLW packages in the Japanese inventory, the product of Japan's spent fuel reprocessing program, around 100 holes could be required, with a bottom internal diameter capable of accepting 43 cm diameter packages. Because DBD is an option that can be considered for any small volume waste, there has been a reawakening of interest recently with respect to several waste-streams, including 'corium' debris (radioactive debris from the collapsed and melted reactor core) from the Fukushima-daiichi NPP.

Advantages to DBD being discussed are that it may not be necessary to separate wastes, small volumes can be accommodated by smaller diameter boreholes and might allow a retrievability option, the characterization of the site and monitoring can be achieved by side-track holes and, in particular, this option might contribute to overcoming the difficulties of handling some wastes at the Fukushima-daiichi NPP. If any of these options were to be pursued further, it is recognized that both the engineering and the safety case development would need major efforts and that finding a site in Japan will continue to present both geological and political problems, as with a conventional GDF.

The Republic of Korea has not decided whether to recycle or dispose directly of spent fuel, so it currently has no national plan on geological disposal of spent fuel, although it has a long-standing R&D programme in this area. Geologically, much of the ROK, indeed the whole Korean Peninsula, may be suitable for consideration for DBD. By 2050, ROK will have between 40,000 and 50,000 tHM of PWR and CANDU spent fuel that will require management. IF DBD were to be implemented, then it is estimated that a programme disposing of between 300-500 tHM/a between 2030 and 2050 would cost between 3 to 6 billion USD, based on a cost of about 20 million USD for construction of each 5 km-depth borehole. Placed in perspective, these costs should be compared with the value of the electricity generated through the use of nuclear reactors through 2050, which is in the range of hundreds of billions of dollars. Whether or not local communities in the ROK would oppose the siting of a DBD facility for spent fuel/HLW remains to be seen, but there are no current legal issues that might affect the practicality of deep borehole disposal of spent fuel in the ROK. Compared with conventional geological disposal, DBD could be more acceptable to local communities. A public consultation process on spent fuel management will critically affect nuclear fuel cycle activities and development, including deep borehole disposal, in the next few coming years.

5. General comments on disposal of SF in deep boreholes

There are several DBD issues that are specific to the use of DBD to dispose of SF. Unlike vitrified HLW, unmodified SF in standard fuel assemblies (FA) is a less stable material to handle, owing to the presence of readily mobilised (including soluble) fractions of several radionuclides in FA gaps and in fuel grain boundaries. If a package containing FAs is breached, then this 'instant release fraction' has the potential to contaminate the fluid in a deep borehole in the event of a serious accident or jam that destroys the container integrity. This may indicate that more robust packages (as would be used in a GDF) may be required. Questions that arise are whether it would be possible to recover the situation, whether the radiological consequences at the surface (during recovery or afterwards) would actually be significant if the borehole were to be sealed and abandoned, and whether it would matter economically to lose a single hole.

A second question is more fundamental to the concept of using DBD to enhance regional safety and nuclear security. In principle, such an aspiration would seem best met by moving SF quickly from the NPP to a point of final, inaccessible disposal. This could be achieved, for example, by moving SF from at-reactor pools to interim dry storage as soon as practicable (e.g. 5 to 10 years), using a centralised, hardened (e.g. underground cavern) dry store that could be protected from natural events and from human attack, and then moving the SF to disposal as soon as it is cool enough to match the design requirements of the disposal facility. Conventional GDFs typically require 50 to 100 years of ex-reactor cooling before disposal. The low-temperature DBD concepts discussed previously and which are attracting most interest (compared to high-temperature, rock melting concepts) could be designed to accept SF earlier: the current US studies are, for example, considering about 25 years. Nevertheless, it is clear that DBD does not offer an 'instant solution' to security issues, as it would still require some decades of interim storage – implying that a security focus should rather be placed on storage facilities and strategies.

A third issue concerns retrievability and resources. SF is a potential resource, whose significance will attract more or less attention depending on the mood of global and national policies on reprocessing and advanced reactor technologies. Despite attempts to build retrievability into DBD design, it must be accepted that DBD is a practically irretrievable disposal solution and, indeed, this is an intention within the origins of the concept – to place hazardous materials beyond human influence. If post-closure retrievability is to be imposed as a requirement on DBD for it to be included in a national programme, it will cause a major diversion of effort away from the critical areas of study on safety case development and borehole engineering and sealing. Retrievability could add considerably to cost and technical difficulty. Consequently, DBD could be seen as a one-way street with respect to flexibility on re-use of SF, compared to a GDF, where retrievability can be made a reasonable prospect (e.g. current designs in Sweden). If there is any likelihood that SF will be needed as a resource over the next century, then DBD is not a solution.

A final SF-related point has to do with the strategy of having a centralised or many small, localised DBD facilities. Clearly, there are attractions to the idea of being able to dispose of SF on-site at a NPP, with facilities at each major NPP complex. However, this will extend the period of interim storage either in the at-reactor spent fuel pond or at a local interim dry storage facility (compared to moving the SF away earlier to a potentially more secure, centralised facility). This appears to be counter to security considerations, although there are clearly design and strategy solutions.

Although the US Nuclear Regulatory Commission (USNRC) has recently stated[12] that, in the USA, the probability of severe accidents or terrorist attacks on SF pools at reactors is low (and the environmental impact risks are thus consequently low), the answer to security concerns nevertheless seems to be to move SF in a timely fashion to high-security, possibly underground, dry storage and to assure a disposal solution that is available in good time for its ultimate disposition. International experience suggests that it takes at least 30 years to move from concept, through siting, design, licensing and construction to an operating GDF. New national programmes might be expected to move forward more quickly now, based on 40 years of international experience. However, DBD will require some significant development and it seems unlikely that following the DBD route rather than the GDF route would accelerate a disposal timetable by more than a decade. Nevertheless, this may be significant in strategic terms. Combined with the potential for much earlier disposal (e.g. 25 rather than 50+ years), this may constitute an ability to go for ‘early’ disposal of SF, with security implications that could attract international support. It would seem worthwhile to quantify this better.

It can be seen that there are several provisos with respect to using DBD for disposal of SF, but these could be clarified or removed by more R&D or by policy decisions. In addition, DBD certainly could have a place in national and regional waste management plans for HLW and other, small-volume wastes (e.g. for on-site disposal of some wastes from the Fukushima-daiichi NPP in Japan). DBD for small amounts of HLW is potentially attractive (e.g., requiring just a few boreholes for a complete national inventory), but few small (and new) NP countries use reprocessing and the current and possible HLW inventories in China, Japan and ROK are large.

For DBD to move forward, work will be required on a number of topics – in particular:

- large-scale testing/demonstration is essential if further progress is to be made – this may happen in the USA;
- a more comprehensive operational and post-closure safety evaluation is essential – this is not an obstacle, as it can be done readily today, with available international expertise and data.

6. Implications for NE Asia and the ASEAN countries

If the issues associated with DBD disposal of SF discussed above were resolved and if the concept were to be a component of a national or an agreed regional strategy for SF management in NE Asia, then there are various scenarios for how this might develop. These are considered in this Section.

Summarising, the possible advantages and attractions of DBD disposal, some of which were discussed above, include:

- earlier disposal of SF, although a long period of pre-disposal storage is still required;
- effectively irretrievable disposal, to satisfy non-proliferation aspirations – barriers to retrieval can be enhanced by appropriate design and management of a DBD facility;
- flexibility, in terms of the number of DBD facilities (which could be regional, national or local – at NPPs) and the times at which they might come into operation, which could be matched to the timetables of the nuclear power programmes of each country;
- flexibility in terms of siting: a characteristic of DBD is that a much wider range of possible siting environments is available than for conventional GDFs – deep boreholes could also overcome some (but not all) of the tectonic stability issues facing siting programmes in countries such as Japan and Taiwan;
- possible economic and strategic benefits for small nuclear power programmes that are not going to opt for reprocessing and will only require disposal facilities for limited amounts of SF;
- the DBD concept is sufficiently non-site-specific to attract an international effort on generic technology aspects, which would be amenable to an international co-operation project: there is potentially interest from a small number of other countries (including the USA) to consider such a shared multinational project.

These advantages and attractions need to be balanced against the currently perceived disadvantages, three of which will have considerable weight in current considerations in the NE Asia context:

- the two largest current and future users of nuclear power in the region (China and Japan), currently have a policy of SF reprocessing, and the ROK would like to reprocess too[13], although this is currently opposed by the USA for reasons of regional security: this means that, although DBD could (possibly more realistically) be deployed for HLW disposal, it does not feature significantly as a possible means of SF management;
- DBD is only a solution for some wastes (SF and HLW) that are destined for geological disposal – a national inventory with significant volumes of ILW will continue to require a conventional GDF and the technical, economic and strategic arguments for whether it is sensible to develop two types of geological disposal facility will depend strongly upon (and vary considerably with) the specifics of national inventory, geological conditions and energy policy;
- the absence of any current projects to study or develop DBD, either for SF or other wastes, in any of the countries concerned.

Regarding the reprocessing issue identified above, it is readily conceivable that national policies on SF management will change. As part of the post-Fukushima evaluation of the future of nuclear power, Japan is already beginning to address the implications for its geological disposal programme for scenarios where there is a diminishing amount of waste produced from a reducing nuclear power programme and where reprocessing could feature less strongly in future, or stop[14]. In this case Japan would need to dispose of both HLW and SF.

The two scenarios for DBD development in the NE Asia region are that one country decides that the concept is sufficiently attractive to develop it as a national solution for some of its wastes or that a group of countries comes together to develop it as a shared solution for specific types of waste.

For a purely national programme, the institutional requirements are no different to those for development of a conventional GDF and a DBD project could be run through the same agencies and research organisations that exist at present. As noted several times above, there is a significant amount of RD&D to be carried out to further the concept. If the technical issues were satisfactorily resolved, perhaps the two strongest drivers that could result in a national programme giving DBD serious consideration would be:

- flexibility and economics: as a modular, time-flexible system, it becomes a significantly less expensive solution for HLW disposal than a GDF, so that even large amounts of HLW can be disposed of at lower cost (i.e. DBD is not just economical for small HLW inventories);
- countries faced with difficulties with respect to tectonic stability and GDF siting find that the DBD concept for HLW allows presentation of a more confident safety case to regulators and the public.

If these drivers are strong enough, then the larger programmes, with predominantly HLW to dispose of, might then consider using DBD for SF as well. Neither of these drivers has yet been explored in depth in a NE Asian context.

Shared solutions to geological disposal involving the major NE Asian programmes seem unlikely at present, owing principally to the size of the individual inventories and for obvious reasons of regional politics. Nevertheless, collaboration on technology development is feasible. Although this article considers mainly the possibilities of collaboration in three of the NE Asian countries, a wider regional collaboration involving all NE Asian countries, plus some or all SE Asian countries with nascent nuclear power programmes, might be envisaged. Current experience in Europe suggests that shared regional solutions for radioactive waste management can help considerably for small or new NP programmes, with shared disposal facilities making sense, economically. As noted above, in the China-Japan-ROK region, the amounts of material involved and other factors make shared disposal facilities look less attractive, but shared R&D could be highly appropriate. For example, the advanced NE Asian nuclear power programmes could offer support to the developing programmes in some of the ASEAN countries, including those to which some countries with advanced nuclear energy programs are now marketing nuclear reactors.

At present, there are no commercial NPPs in SE Asia, but several ASEAN countries have studied the possibility of introducing nuclear power, although most of these plans are on ice after the Fukushima disaster. The 2013 World Energy Outlook report from OECD/IEA[15] on the region concluded that nuclear power has a limited role in SE Asia over the period evaluated (to 2035):

"This reflects the complexities of developing a nuclear power programme and the slow progress to date of most countries that have included nuclear in their long-term plans. Vietnam is the most active and is currently undertaking site preparation, work force training and the creation of a legal framework. Moreover, Vietnam has signed a co-operative agreement (that includes financing) with Russia to build its first nuclear power plant, with construction expected to begin in late 2014 and nuclear to enter the power mix before 2025. Thailand includes nuclear power in its Power Development Plan from 2026. While these plans could face public opposition, the country has very limited indigenous energy resources, which is expected to be a key driver behind its development. We project Thailand to start producing electricity from nuclear power plants before 2030."

The current status of nuclear power development across the whole of NE and SE Asia is summarised in the Table below, using data from the World Nuclear Association.

	Numbers of Nuclear Power Units			
	Operating	Under Construction	Planned	Proposed
NE Asia				
China	17	30	59	
Japan	50*	3	10	
Republic of Korea	23	5	6	
Taiwan	6	2		
SE Asia (ASEAN)				
Indonesia	0	0	2	4
Philippines	0	0	0	1
Thailand	0	0	2	4
Vietnam	0	0	4	6
*Nearly all of Japan’s operable NPPs were all out of operation at the time of this writing, undergoing regulatory stress tests				

It can be seen that the NE Asian countries will completely dominate nuclear power in the East Asian region for at least the next 20 to 30 years, with about 200 NPPs potentially being operational in that period, compared to perhaps 10 – 20 in the ASEAN countries. The amounts of material being generated for disposal will be commensurate.

The question then arises whether DBD of SF could be a suitable shared solution for the ASEAN countries that could be developed with technical assistance from the NE Asian countries (if they were pursuing DBD) or from elsewhere – e.g. if the USA progresses the technology further. This scenario has not been explored from a technical, economic or political viewpoint. In any case, given the current slow progress towards well-established and co-ordinated nuclear development or regulatory infrastructure in the ASEAN region, serious consideration of this scenario seems premature.

A final scenario is one in which DBD is developed in a NE Asian country (for either HLW or for HLW and SF) and offered as a service to ASEAN countries for SF disposal, perhaps driven mainly by a desire to enhance Asian nuclear security as a whole. The potential to make DBD highly irretrievable is essential to the security objective here.

As a final, bounding consideration for all these discussions, one might ask why DBD has not advanced beyond conceptual evaluations over the last 30 years. The answer seems to be that national GD programmes consider that they already have an entirely adequate, safe and secure solution in their conventional GDF plans, and that this solution is supported by decades of independent and shared concept development and R&D. DBD is seen as an unhelpful digression that would require new R&D with an uncertain outcome. This situation is reflected not only in a lack of interest from national GD programmes, but also in some resistance to the concept. Thus, with the exception of current developments in the USA, any new DBD programme in the Asia-Pacific region might initially expect to receive rather weak support from elsewhere.

III. REFERENCES

[1] Sapiie, B. and Driscoll, M. J., *A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Waste.* Massachusetts Institute of Technology Report MIT-NFC-TR-109, 2009.

[2] Brady, P. V., Arnold, B. W. Freeze, G. A., Swift, P. N., Bauer, S. J. Kanney, J. L., Rechard, R. P. and Stein, J.S., *Deep Borehole Disposal of High-Level Radioactive Waste*. Sandia National Laboratory, Albuquerque, USA. Report No: SAND2009-4401. 75 pps, 2009.

[3] von Hippel, D. and Hayes, P. *Borehole disposal of nuclear spent fuel and high level waste as a focus of regional East Asia nuclear fuel cycle cooperation*. Nautilus Institute Report, 2010. Available at:
http://www.nautilus.org/publications/essays/napsnet/reports/Deep%20Borehole%20Disposal%20von%20Hippel%20-%20Hayes%20Final%20Dec11-2010.pdf

[4] Gibb, F. G. F., K.J. Taylor & B.E. Burakov. "The 'granite encapsulation' route to the safe disposal of Pu and other actinides". *Journal of Nuclear Materials*, 374, 364-369, 2008.

[5] Gibb, F. G. F., N. A. McTaggart, et al., "High-density support matrices: Key to the deep borehole disposal of spent nuclear fuel". *Journal of Nuclear Materials* 374: 370-377, 2008.

[6] Hoag, C. I. *Canister design for deep borehole disposal of nuclear waste*. Dept of Nuclear Engineering. Cambridge, MA, MIT, 2006.

[7] Brady, P. V. and Driscoll, M. J. *Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC*, 2010. Available at: www.mkg.se/uploads/SNL_MIT_borehole_workshop_report_final_100507.pdf

[8] Arnold, W. B., Vaughn, P., MacKinnon, R., Tillman, J., Nielson, D., Brady, P., Halsey, W. and Altman, S. (2012). *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal*, Sandia National Laboratories, Report SAND2012-8527P.

[9] Gibb, F. G. F., "Looking down the bore". *Nuclear Engineering International*, March 2010. At: http://www.neimagazine.com/storyprint.asp?sc=2055863, 2010.

[10] Filbert, W., Bollingerfehr, W., Heda, M., Lerch, C., Niehues, N., Pöhler, M., Schulz, J., Schwarz, T., Toussaint, M. and Wehrmann, J., *Optimisation of the direct disposal concept by emplacing SF canisters in boreholes.* DBE Technology Report No. TEC-10-2009-AB. 94 pps, July 2010.

[11] Beswick, J., *Deep borehole disposal of radioactive waste.* Presentation to the 11th RWIN (Radioactive Waste Immobilisation Network) meeting, Sheffield, April 2009. Available

at: http://www.rwin.org.uk/presentations.html,

[12] USNRC (2013). *Waste Confidence Generic Environmental Impact Statement.* United States Nuclear Regulatory Commission. NUREG-2157, 585 pps.

[13] Dalnoki-Veress, F., Pomper, M., Lieggi, S., McCombie, C. and Chapman, N. (2013). The Bigger Picture: Rethinking Spent Fuel Management in South Korea. James Martin Center for Nonproliferation Studies (CNS). Occasional Paper 16, 104 pps. ISBN 978-0-9892361-1-9

[14] Kawamura, H and McKinley, I. G. (2013). Direct disposal of spent fuel: developing solutions tailored to Japan. In: Proceedings of 15th International Conference on Environmental Remediation and Radioactive Waste Management (ICEM'13), Brussels. American Society of Mechanical Engineers. Paper ICEM2013-96066.

[15] International Energy Agency (2013). *Southeast Asia Energy Outlook*. World Energy Outlook Special Report. OECD/IEA, Paris, 138 pps.

[4] Åhäll, K-I, *Final Deposition of High-level Nuclear Waste in Very Deep Boreholes: an evaluation based on recent research of bedrock conditions at great depth*s. MKG Report No 2. Miljöorganisationernas kärnavfallsgranskning, Stockholm, Sweden, 2010.

[5] Beswick, J., *Status of technology for deep borehole disposal*. Contractor report to UK Nuclear Decommissioning Authority. 93 pps, 2007.

IV. NAUTILUS INVITES YOUR RESPONSES

The Nautilus Peace and Security Network invites your responses to this report. Please leave a comment below or send your response to: nautilus@nautilus.org. Comments will only be posted if they include the author's name and affiliation.

View this online at: https://nautilus.org/napsnet/napsnet-special-reports/deep-borehole-dispos-l-of-spent-fuel-international-developments-and-implications-for-ne-asia/

Nautilus Institute
2342 Shattuck Ave. #300, Berkeley, CA 94704 | Phone: (510) 423-0372 | Email: nautilus@nautilus.org