Deep Borehole Disposal of Spent Fuel and Other Radioactive Wastes

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by Neil A. Chapman

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I.INTRODUCTION

This report by Neil Chapman "provides a review of the status of international research and policy on the use of very deep boreholes (several kilometres in depth) for the disposal of radioactive wastes." While reviewing numerous studies on deep borehole disposal of spent fuel, HLW and other radioactive wastes, Chapman finds that "a key gap continues to be a comprehensive operational and post-closure safety assessment of DBD." He also finds that "the lack of full-scale trials of certain aspects of the technology (not necessarily at envisaged disposal depths) is holding up further development."

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The views expressed in this report do not necessarily reflect the official policy or position of the Nautilus Institute. Readers should note that Nautilus seeks a diversity of views and opinions on significant topics in order to identify common ground.

II. special report by Neil A. Chapman

Deep Borehole Disposal of Spent Fuel and Other Radioactive Wastes

An International Overview and Commentary on Developments in China, Japan and the Republic of Korea

Introduction

This short note provides a review of the status of international research and policy on the use of very deep boreholes (several kilometres in depth) for the disposal of radioactive wastes. The first part on technical aspects and international experience is based in part on a review carried out by the author for the UK Nuclear Decommissioning Authority.

The driver behind the Nautilus Institute study of deep borehole disposal is an exploration of ways of disposing of spent fuel (SF) from nuclear reactors in East Asia to support a prospective nuclear weapons free zone in the region and avoid security and sustainability dilemmas associated with the management of its rapidly growing quantities of SF.

The concept of deep borehole disposal (DBD) of spent fuel, HLW and other radioactive wastes has been discussed actively for many decades. As pointed out in 2010 by Murphy and Diodato of the US Nuclear Waste Technical Review Board [[1]], DBD is a "technically viable type of geologic disposal" (i.e., they consider it a variant of geological disposal).

DBD involves emplacement of waste packages in the bottom sections of deep 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 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 ILW streams). Consequently, all work has concentrated on the use of DBD for disposal of HLW and SF (plus conditioned Pu waste forms).

The most comprehensive recent evaluations of DBD have taken place in the USA. A review was carried out by the Massachusetts Institute of Technology [[2]], an extensive study was made by Sandia National Laboratories (SNL) [[3]] and a recent evaluation was prepared by von Hippel and Hayes of the Nautilus Institute [[4]]. The drivers for the SNL and MIT reviews have mainly resulted from the demise of the Yucca Mountain Project. 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.

After the effective termination of the Yucca Mountain project, an update to the 1984 (revised in 1990) 'Waste Confidence' ruling was considered necessary in order to show that a solution for spent fuel management from a prospective programme of new nuclear power reactors would still be possible. A measure of the renewed interest in DBD in the current discussions in the USA is that two of the US Nuclear Regulatory Commission commissioners referred specifically to DBD when deliberating their positions on this waste confidence update, in September 2009 [[5]]. Although DBD received no mention in the final update to the waste confidence decision in December 2010 [[6]], the USDOE Office of Nuclear Energy had reopened consideration of the DBD option in 2009.

Elsewhere in the world, DBD-related work has developed slowly, although interest has remained

active. In December 2006, Åhäll reviewed [[7]] 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 was a continuing programme of research work at the University of Sheffield, mainly focussed on thermal modelling of the so-called 'high temperature' 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 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 [24].

In all of the work listed above, 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. This, along with the findings of the studies mentioned above, is discussed in Section 2.

DBD Concepts and Technologies

The various methods currently under consideration for DBD were presented by Arnold and co-workers [[8]] and Gibb [[9]] in early 2010. Gibb describes 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[1]. Figure 1 illustrates the three concepts defined by Gibb (two

low temperature concepts and one high temperature concept).

[caption id="attachment_31544" align="aligncenter" width="409"]

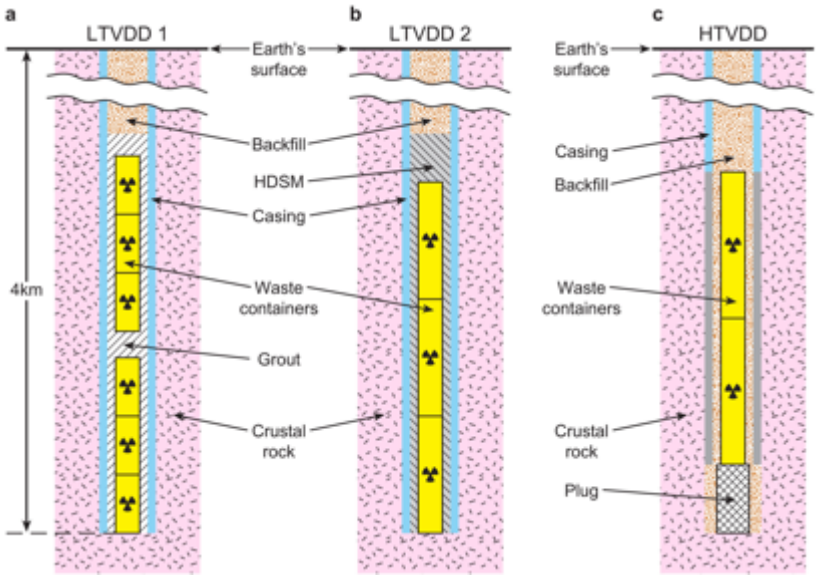


Figure 1: Schematic illustrations of the two low temperature (left and centre) and one high temperature (right) concepts defined by Gibb and described in the text. The HTVDD concept is being less actively considered internationally than the low temperature concepts.[/caption]

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. Recent heat flow modelling by Gibb and co-workers [[10]; [11]] 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 wasteforms. Gibb and colleagues [[12]] suggest a 'granitic' wasteform (although the concept would be suitable for any ceramic or silicate-based wasteform) and also suggests that boreholes for disposal of Pu waste packages could be of much smaller diameter (e.g. < 0.3 m) than for HLW or SF disposal.

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 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 [[13]] 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.

Recent work in the USA

In the last two years the disparate work on DBD that has occurred over several decades has been brought into sharper focus by the above-mentioned collaborative work being performed by Sandia National Laboratories (SNL) and the Department of Nuclear Science and Engineering of the Massachusetts Institute of Technology (MIT) in the USA. This co-operation led to an international review workshop on DBD in March 2010 which 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 over recent years [[14]; [15]; [16]; [17]; [18]; [19]] and the results of the March 2010 workshop were outlined by Brady and Driscoll [[20]]. Prior to this, much of the most recent information from the US studies was assembled in a 2009 report by SNL, which also reported the results of the first performance assessment that has been carried out for DBD, using techniques common to those used for conventional GD.

The Sandia 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".*

As noted above, this study was the first to attempt a quantitative performance assessment of DBD, although it was relatively 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 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).

The SNL report concluded that further work is needed to test preliminary observations about long-term performance, including work on:

- scenarios to look at other release pathways;
- more accurate modelling of the thermal-hydrogeological-chemical-mechanical behaviour of the borehole and surrounding rock;
- seal design;
- engineered materials that sequester iodine;

- performance assessment of arrays of multiple emplacement holes.

Since the publication of this study, new work on coupled THCM modelling of DBD concepts has been reported by Arnold and co-workers at the Sandia group [[21]], which looks at volumetric strains and displacements in the rock surrounding the disposal borehole.

Further important conclusions of the 2009 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. The 2009 summary [2] focuses 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.

Since 2003 the main focus at MIT has been on disposal of separated minor actinides and ‘troublesome’ fission products (e.g., Tc-99, I-129) as a strategy for facilitating conventional disposal in near-surface mined repositories. A ceramic wasteform containing minor actinides, plus Tc-99 and I-129, emplaced in a 2 km deep waste zone could holds 100 reactor-years worth per borehole, in which case only sixty boreholes could deal with the minor actinides of the current US one-hundre--reactor fleet over their (extended) lifetime of sixty years. This approach, however, presupposes that a major spent fuel reprocessing program becomes part of US fuel cycle policy. Such a policy would have considerable and far-reaching technological and economic implications, requiring major new facilities that will eventually need to be decommissioned, as well as affecting the types and volumes of associated wastes and the overall balance of current and far-future radiological impacts.

At the March 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).

The perceived disadvantages 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, as mentioned earlier 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.

Brady and Driscoll [3] record 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. Characteristics of the interface between the seals and the borehole wall will be particularly important. 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 reference design concept to provide a baseline for evaluating performance and impacts of alternative approaches may be useful.

On retrievability, the workshop concluded that this should be maintained up to the time the borehole is sealed. A slotted emplacement zone hole liner could be considered to facilitate grouting the liner to the borehole wall and to the canisters. This would also provide support against crushing of bottom-most canisters and permit use of the simplest configuration: filling a single-branch vertical hole in stages, allowing the grout (cement) to dry before inserting the next upper set of canisters.

Examples of favourable site characteristics include tectonic stability, homogeneity of features such as permeability, high salinity of porewater at depth, and absence of over-pressured zones. Site characterisation will be an important aspect of licensing. The use of natural analogues and evidence such as U-Pb indicators of transport can make major contributions to evaluating radionuclide mobility. Both small and full-diameter boreholes can be used for acquiring key scientific information and for demonstrating key engineering and procedural features.

A list of R&D questions was generated and prioritised, the first ten of which can be summarised as follows:

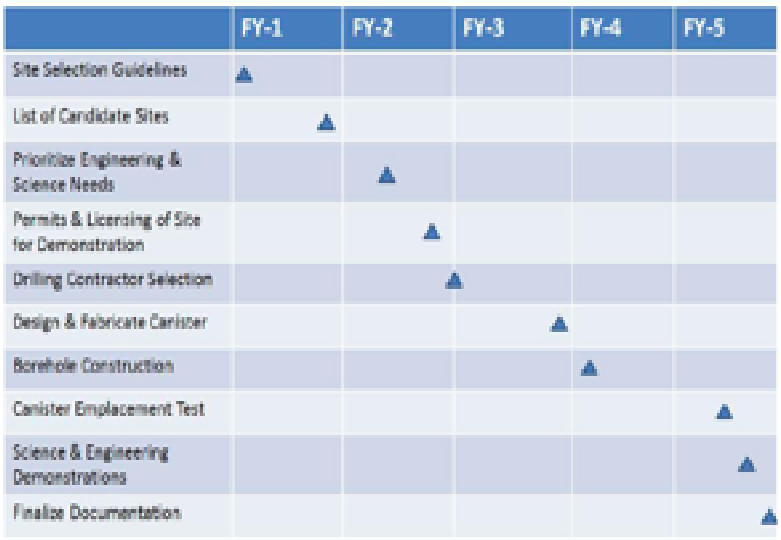
1. Design Pilot Tests: (a) at shallow depth, for testing emplacement engineering and (b) at full depth to prove DBD can be done and containers recovered (both tests at actual diameter).
2. Borehole sealing/drilling: assess what happens if the borehole cannot be sealed and how many holes could fail or have to be abandoned.
3. Geochemistry: natural indicators of deep hydrogeochemical stability and heterogeneity, including the effects on performance and the sensitivity to drilling techniques.
4. Drilling: assess the link between drilling and disturbed rock permeability to evaluate whether the borehole environment and performance is deleteriously perturbed by drilling/emplacement.
5. Reliability and Surveillance: how to demonstrate key aspects of borehole and emplacement system design at depth, including sensor performance and sensor parameter targets.
6. Hydrogeology: establish lithological heterogeneity controls on large-scale fluid convection in the borehole disturbed zone.
7. Waste Form and Package Design: materials for packaging; the use of consolidation for SF.
8. Downhole Testing: tools that may need development, e.g. acoustic and electromagnetic techniques that allow continuous surveillance of vertical fluid motion.
9. Geology: how to detect, predict or pre-screen for geopressured zones at depth and how to determine if and when this is important.
10. Drilling: establish the value of casing all the way down the borehole.

In respect of the primary recommendation that a pilot demonstration should be performed, it is

useful to note the conclusions of the 2009 Sandia report that preceded the workshop, which states:

> *"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."*

Sandia has prepared proposals for such pilot studies, which could be presented for consideration should DBD obtain sufficient support as part of the US programme. This is likely to generate practical information on the feasibility of DBD that has so far not been available. The outline plan is presented in the form of a road-map for DBD research produced by Sandia NL [29], whose proposed schedule is shown below:



Other international developments

Independently of the SNL developments, Gibb has proposed an outline approach for large scale testing of DBD technology in a UK context [[22]], 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 of the outcomes. 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, followed by installation of cementitious grout. The emplacement, melting and solidifying of a HDSM could also be tested, with the waste package, casing and borehole instrumented to monitor conditions and evaluate the accuracy of heat flow modelling. An important demonstration would be the cutting of uncemented 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 GDF. DBE Technology [[23]] has carried out development and full scale testing of package handling technologies for placing packages in such boreholes 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, in 2007, to an NDA sponsored evaluation of the deep, relatively large diameter borehole technology that would be needed for DBD by Beswick [[24]]. Subsequently, in 2009, Beswick made an updated presentation of DBD technology issues [[25]], 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 vertical drilling systems can now assure verticality, notwithstanding stress breakout influences. 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. Summarising the development needs, Beswick identifies:

- large diameter drilling tools and drill string;
- casing design and installation procedures for large diameters;
- casing design for deployment zone;
- cementation methods for upper large diameter casing;
- waste deployment procedure and handling tools;
- annulus sealing in the deployment zone;
- upper borehole seals and near surface abutment.

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, reducing significantly with subsequent holes. The 2009 MIT summary report [2] 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.

Possible applications in national GD programmes

As noted in Section 2, the US national programme is currently considering how best to manage SF in the future, following the effective closure of the Yucca Mountain (conventional GDF) project and the national laboratories have devoted resources to evaluation of DBD. The lead organisation promoting the concept is SNL, in collaboration with scientists at MIT. SNL is poised to propose (to the Department of Energy) pilot tests and demonstrations of aspects of the technology, should DBD emerge from current policy deliberations as an option worth pursuing. In this case, it would seem likely that other topics from the list of R&D requirements discussed in the previous section 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 relatively low level of activity for many years, as a possible alternative to conventional GD for SF. There is a requirement from SKB to consider and report on alternatives when it makes a license application for disposal and, given the interest in DBD displayed by Swedish NGOs, it seems likely that the concept will be discussed actively over the next few years as part of the licensing and approvals process. It seems unlikely, however, that any further development of the concept in Sweden will arise as a result of these formal procedures.

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 [4]. SF inventories in the region are growing rapidly and the 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.

A parallel study by Kang [[26]] has looked more specifically at the DBD option for disposal of the SF generated by the Republic of Korea. Current plans for ROK reactor deployment mean that approximately 51,000 t of spent PWR fuel and 20,000 t of spent HWR fuel will be generated over the lifetimes of the NPPs by 2030. It was estimated (very approximately) that the cumulative cost of DBD disposal of this cooled spent fuel would be in the range of about $4 to $9 billion from 2030 through 2050.

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 geological repositories, 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 geological repository is heavily influenced by the tunnel lengths required for conventional disposal of HLW and SF containers, so this approach could influence repository 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 possibly no requirement to overpack HLW at all) 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 in any country, as they are closely related to DBD safety case development, which has only just begun to be worked upon. 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 repository, 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 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.

Other combinations of disposal options can be considered in developing strategic scenarios and there are several scenarios that might be considered for combinations of different materials to be disposed of and whether and when they are directed to a repository or to DBD.

Possible Future Developments

The potential for the US programme on DBD to increase in pace over the next few years may be the most significant factor in the near future. The key drivers that may emerge and increase the prominence of DBD would be:

- successful pilot testing of practical borehole and waste package handling methodologies and technologies in the US programme;
- launch of a more active R&D programme in the USA, addressing the central issues of borehole sealing and further developing safety assessment scenario analysis;
- clearer concepts emerging for the scale and nature of site investigations required for a DBD facility.

Current Status in China, Japan and the Republic of Korea

At the May 2013 Nautilus meeting in Beijing, updates on work or policy considerations of DBD were presented for each country. Yun Zhou (Harvard University, USA) explained that, in China, deep borehole disposal was not 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 Areva (France) for the development of a large-scale (800 tHM/a) 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 and China needs an Atomic Energy Law and regulations to cover nuclear waste management, disposal and a possible spent fuel disposal fund. Additional funding is required for radwaste R&D, which has so far not attracted a high priority. Future developments would be enhanced and facilitated by increased international co-operation.

The situation in Japan was presented by Tomochika Tokunaga (University of Tokyo). Although NUMO (the Nuclear Waste Management Organization of *Japan*) identified DBD as an option in 2004, there has been little interest in the approach and no work has been carried out by NUMO. Japan has several very deep holes, constructed by METI (the Ministry of Economy, Trade and Industry) in the 1990s, e.g.: Shin-Takenomachi (1993) to 6,310 m, with a cased diameter of ~17.8 cm OD and a bottom temperature of 197 C; Mishima (1992) to 6,300 m with a bottom temperature of 226 C; Higashi-kubiki (1989-1990) to 6,001 m, cased to 5000 m at about 24.4 CM OD and uncased below that. 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 geological disposal. These examples of test drilling in Japan are all slimmer holes than would be needed for emplacing, for example, a vitrified HLW package of 43 cm diameter. With 40,000 HLW packages, around 100 holes could be required. The difficulty of retrieval is seen as an issue, if such a requirement would be placed on the disposer. Nevertheless, 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:

- debris inside the Fukushima-daiichi NPP;
- fuel/spent fuel in the pool at Fukushima-daiichi;
- radioactive wastes from research institutions;
- ^{129}I (^{14}C) in TRU waste.

Advantages 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 will continue to present problems, as with a conventional GDF.

An update on the situation in the Republic of Korea was given by Jungmin Kang (Korea Advanced Institute of Science and Technology, or KAIST), who pointed out the over-arching consideration that, since ROK has not decided whether to directly dispose of or recycle spent fuel, it currently has no national plan on geological disposal of spent fuel either, 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 (with a start-up disposal of over 2000 tHM) would cost between 3 to 6 billion USD. A borehole is assumed to accommodate 200-400 canisters containing a total of about 100-200 tHM of spent PWR fuel, or about 1,600-3,200 canisters containing about 32-64 tHM spent HWR fuel. Cost estimation is based on a cost of about 20 million USD for construction of each 5 km-depth borehole. 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. Considering its potential safety superiority when compared with conventional geological disposal, DBD could be more acceptable to local communities. A public consultation process on spent fuel management will start soon, which will critically affect nuclear fuel cycle activities and development, including deep borehole disposal, in the ROK in the coming years.

Conclusions

An overview presentation by Neil Chapman made a number of observations about the potential role of DBD of SF in the China-Japan-Korea region, as envisaged in the Nautilus Institute project.

There are several DBD issues that are specific to its use 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 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 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 loose 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 to be 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 above 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 certainly 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. In the author's opinion, if retrievability is to be imposed on DBD as a demand on its inclusion 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 on 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 is 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 there being facilities at each major NPP complex. However, this will extend the period of interim storage either in the AR-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.

The best answer to security concerns 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. 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 quantifying 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 firm policy considerations. In addition, DBD certainly could have a place in national and regional waste management plans for HLW and other, small-volume wastes (e.g. considerations in Japan and ROK). 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.

How might co-operation help? One attraction is that the DBD concept is sufficiently non-site-specific to attract an international effort on generic technology aspects. This would be amenable to an international co-operation project and there is potentially sufficient interest from a number of countries to consider such a shared multinational project. This would need a host country – for the engineering trials.

Current experience in Europe suggests that shared regional solutions for radioactive waste management can help considerably for small NP programmes, with shared disposal facilities making sense, economically. In the China-Japan-ROK region, the amounts of material involved make shared disposal facilities look less attractive, for many reasons, but shared R&D could be highly appropriate.

In conclusion, one might ask why DBD has not advanced much 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 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.

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[1] Nevertheless, rock-melting concepts continue to attract some attention and Ojovan et al. [27] proposed using high-density, self-sinking capsules that would melt their way down into deep rock

formations as a means of disposing of some the highest activity (albeit, short half-life) spent radiation sources that are used in industrial and medical applications and as thermoelectric generators. This concept was recently adapted [28] as a possible scientific research tool, whereby a self-sinking tungsten-clad capsule could be used to probe Earth's mantle to depths of tens of km, with information being retrieved by remote acoustic monitoring of the capsule's interaction with the rock.

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