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Beswick, Gibb and Travis

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Deep borehole disposal of nuclear waste: engineering challenges

1 **A. John Beswick** MSc, DIC, CEng, MICE, FGS
Member SPE; Director, Marriott Drilling Group

2 **Fergus G. F. Gibb** BSc, PhD, FGS
Emeritus Professor, Department of Materials Science and Engineering, University of Sheffield, Sheffield, UK

3 **Karl P. Travis** BSc, PhD, CChem, MRSC
Senior Lecturer, Department of Materials Science and Engineering, University of Sheffield, Sheffield, UK


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In recent years, geological disposal of radioactive waste has focused on placement of high- and intermediate-level wastes in mined underground caverns at depths of 500–800 m. Notwithstanding the billions of dollars spent to date on this approach, the difficulty of finding suitable sites and demonstrating to the public and regulators that a robust safety case can be developed has frustrated attempts to implement disposal programmes in several countries, and no disposal facility for spent nuclear fuel exists anywhere. The concept of deep borehole disposal was first considered in the 1950s, but was rejected as it was believed to be beyond existing drilling capabilities. Improvements in drilling and associated technologies and advances in sealing methods have prompted a re-examination of this option for the disposal of high-level radioactive wastes, including spent fuel and plutonium. Since the 1950s, studies of deep boreholes have involved minimal investment. However, deep borehole disposal offers a potentially safer, more secure, cost-effective and environmentally sound solution for the long-term management of high-level radioactive waste than mined repositories. Potentially it could accommodate most of the world's spent fuel inventory. This paper discusses the concept, the status of existing supporting equipment and technologies and the challenges that remain.

1. Introduction

Since the 1940s, radioactive wastes have been accumulating in many countries at ever increasing rates. Despite the hazards and risks posed by such materials, no facility yet exists anywhere in the world for the disposal of spent nuclear fuel and other high-level wastes (HLW). With the ever increasing demand for energy and the world focussing on low carbon sources, it is clear that nuclear power must play a significant part for the foreseeable future, especially as the scarcity of cheap fossil fuels and environmental concerns threaten the sustainability of economies. However, it is inconceivable that this could happen without a solution to the problem of how to dispose of spent nuclear fuel and other HLW and acceptable radioactive waste disposal remains a pressing and critical issue for mankind.

Disposal in deep boreholes was considered over 50 years ago (NAS, 1957), but was rejected in favour of mined and engineered repositories at depths of only a few hundred metres largely because, at the time, the technology for drilling large enough diameter holes to depths of a few kilometres did not exist. After nearly 60 years of research and development (R&D) programmes spread across many countries and costing billions of dollars, mined repositories are still not without their problems and an operating facility is still some decades away, with the Finnish repository at Onkalo likely to be the first. This dilemma is highlighted by the recent cancellation of the Yucca Mountain repository in the USA and the challenges to Svensk Kärnbränslehantering's (SKB) application for a spent fuel repository at Forsmark in Sweden, together with the failure to progress a geological disposal facility in West Cumbria in the UK.

Advances in deep drilling technology over the past 20–30 years have led to the reconsideration of deep borehole disposal (DBD), notably in the USA (Brady *et al.*, 2009; MIT, 2003; Woodward-Clyde Consultants, 1983), in Sweden (Juhlin and Sandstedt, 1989; Juhlin *et al.*, 1998) and in the UK (Beswick,

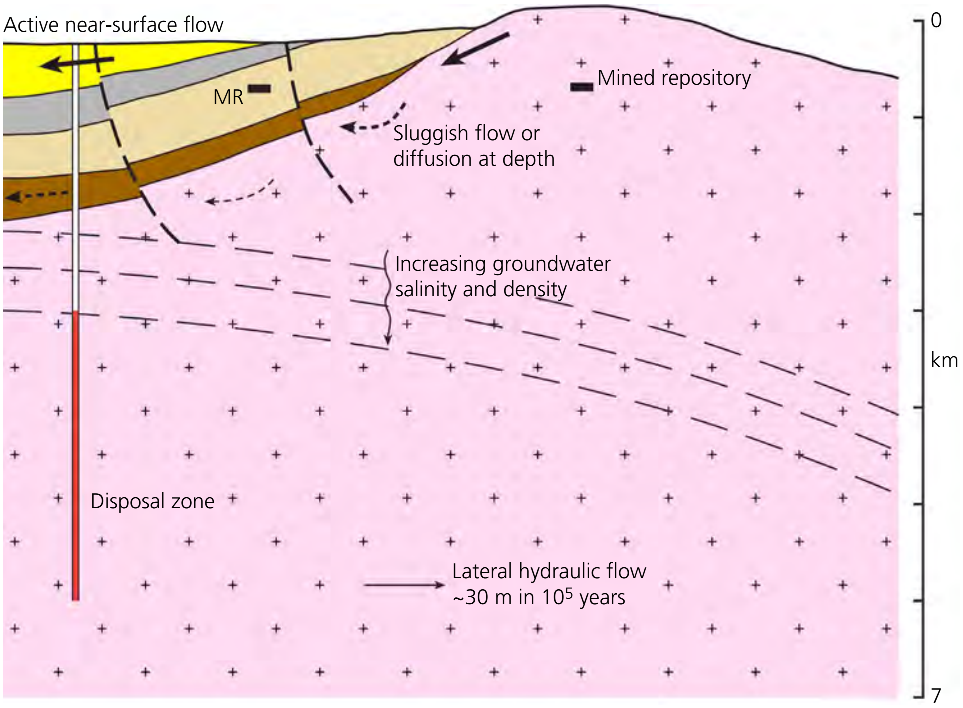

Figure 1. Schematic diagram of the deep borehole disposal concept (not to scale). Modified after Chapman and Gibb (2003)

2008; Chapman and Gibb, 2003; Gibb, 1999, 2000; Nirex, 2004) and it is now emerging as a realistic alternative to mined repositories for spent nuclear fuel, reprocessing waste and plutonium. This is particularly so in the USA where the Department of Energy, following the recommendations of a presidential Blue Ribbon Commission, has initiated a programme, led by Sandia National Laboratories, to investigate DBD with the objective of taking it to a full-scale demonstration with non-active waste.

While DBD has the potential to offer a safer, more secure, cost-effective and environmentally sound disposal route that could possibly be implemented earlier than mined repositories, a number of technical challenges remain (e.g. NWTRB, 2013). This paper considers these and discusses how they are being, or could be, addressed.

2. Background

The DBD concept (Figure 1) involves sinking large-diameter cased boreholes 4–6 km into the granitic basement of the continental crust and deploying packages of radioactive waste in the lower reaches of the hole before sealing it above, or at the top of, the disposal zone and backfilling the rest of the borehole. With a geological barrier an order of magnitude deeper than mined repositories, it makes use of the very low bulk hydraulic conductivities ($<\sim10^{-11}$ m/s) usually found at such depths, even in fractured rocks. It also capitalises on the likelihood that any fluids in the rocks at these depths will be saline brines (Moller *et al.*, 1997; Stober and Bucher, 1999, 2004) out of physical and chemical contact with the near-surface circulating groundwaters, which rarely extend below 1 or 2 km. This isolation is due to a density stratification (Arnold *et al.*, 2013; Bucher and Stober, 2000) that has often been stable for many millions of years (Fehn and Snyder, 2005) and is likely to remain so far into the future, unaffected by climate changes, sea-level rises, glaciations and even earthquakes. This density stratification, combined with low lateral flow rates and almost non-existent vertical flow, ensures that any radionuclides that eventually escape from the waste packages and disposal zone will go effectively nowhere in the 1 Ma or so required for most HLWs to become radiologically harmless, and certainly not back up to the biosphere.

Compared to mined repositories as a route for the long-term management of HLWs, DBD offers many potential advantages in addition to the greater isolation and safety described above (Chapman and Gibb, 2003; Gibb *et al.*, 2008b; MIT, 2003). At a few tens of millions of dollars per borehole, a DBD programme is likely to be significantly more cost effective than a mined repository, estimates for which range from hundreds of millions to tens of billions of dollars. Furthermore, the nature of a mined repository requires that high 'up-front' costs are incurred before any waste is emplaced and substantial operating costs follow, possibly for hundreds of years. By contrast, DBD is effectively a 'pay as you go' scheme that allows a small disposal programme to be expanded as required or a large one to be terminated at any point (and for whatever reason) without any significant further cost.

It should be much easier to find a geologically suitable site for DBD than for a mined repository because much of the continental crust is underlain at appropriate depths by granitic basement with low hydraulic conductivities. In contrast to the detailed site characterisation of a large volume of rock required for a mined repository, for DBD it is only necessary to identify a modest, relatively homogeneous, volume of a suitable rock at appropriate depths with low bulk hydraulic conductivities and low differential stress regimes in an area with a density stratified saline hydrogeology. The planning and construction of a mined repository for nuclear wastes takes many decades (e.g. the current timescale for a UK repository is to open in around 2040 and take its first HLW or spent fuel by 2075). As a 4 km-deep borehole with a useable diameter of approximately 0·5 m could be drilled in under a year (Beswick, 2008) and filled and sealed in another 2 or 3 years, the first DBD could be completed less than 5 years after a successful demonstration of the concept, identification of a site and granting of regulatory approval. Site identification, with its socioeconomic–political aspects, is the most likely cause of delay, but the greater depth of burial, safety and availability of technically suitable sites for DBD could facilitate public and political acceptance.

One of the major problems associated with mined repositories relates to the transport of wastes. A serious political, economic and technical difficulty faced by the cancelled US federal repository at Yucca Mountain was the need to transport spent fuel from all over the continental USA to Nevada through many non-nuclear states by means of an incomplete transport infrastructure. By contrast, DBD could reduce or even eliminate the transport issue through its potential for dispersed disposal. The footprint of an individual borehole is tiny and even for a multi-borehole array it is quite small. Heat flow modelling of DBD of quite high heat-generating wastes (Gibb *et al.*, 2012) has shown that boreholes need be only a few tens of metres apart. Consequently, a DBD programme could involve many small sites with only one or a few boreholes each, even extending to individual nuclear power plants disposing of their own wastes on or near site. All that is needed is suitable geology nearby.

Disposal of high heat-generating wastes, such as high burn-up spent nuclear fuel, creates problems for mined repositories, necessitating increased spacing of the disposal vaults/tunnels and, because of limitations imposed by engineered barrier materials, can require protracted post-reactor cooling before disposal – in some cases for up to 100 years and more (NDA, 2009). By contrast, DBD is relatively insensitive to both the composition of the waste (as long as it is solid) and its heat output (Gibb *et al.*, 2012) thus allowing relatively early disposal of heat-generating wastes without any increase in the volume of host rock required.

The environmental impact of DBD is considerably less than a mined repository. Irrespective of the number of boreholes at any one site, they would probably be drilled and filled one (or at the most two) at any one time. Consequently, the surface facilities and disruption would be small compared with the construction and operation of a repository. More importantly, they would be transient. Once a borehole is sealed and the rig removed the environmental impact of a backfilled borehole is effectively zero, so the environmental disruption from any one hole is likely to last for less than 2 or 3 years. Contrast this with mined repositories, which would take decades to construct and could remain open and operational for many decades or even hundreds of years if new-build spent nuclear fuel is to be accommodated.

The March 2011 accident at Fukushima in Japan was a timely reminder of the need for all nuclear installations to be able to withstand both the direct and indirect effects of tectonic events. While the near-field (engineered barrier) containment of a mined repository could be designed to survive small earthquakes, the only safeguard against major seismic events is to avoid faults that could be reactivated and site the repository well away from fault zones that could host a magnitude 6+ event. DBD, on the other hand, is inherently secure against even high-magnitude tectonic events because seismic shaking and shear waves would have little effect on the density stratification of saline fluids in the host rock. Consequently, while these might damage the integrity of the containers, disrupt the near-field barriers in the borehole and fracture the surrounding host rock, they would not destroy the isolation of the fluids into which the radionuclides might subsequently be leached.

The main perceived disadvantage of DBD is the near irretrievability of the wastes. Until the borehole is sealed the waste packages could be recovered almost as easily as they can be emplaced, but if individual packages are sealed in or once the hole itself is sealed above the disposal zone, recovery of the packages becomes very difficult and expensive. In countries where retrievability of the wastes beyond the point of closure of the repository (or borehole) is a legal or regulatory requirement DBD is not really an option. Against this, there are some potential wastes for which security is paramount; for example, fissile materials such as highly enriched uranium and plutonium. As covert recovery of packages from a DBD would not be possible given the scale of any such operation, the security offered by this form of disposal is unbeatable, making it the ideal way of putting such materials beyond illegal use and as a safeguard against nuclear weapons proliferation (Gibb *et al.*, 2008b; Halsey *et al.*, 1995; Von Hippel *et al.*, 2012).

Many different variants of the basic DBD concept have been proposed (e.g. Brady *et al.*, 2009; Gibb, 2000; Gibb *et al.*, 2008a, 2012; Hoag, 2006; Juhlin and Sandstedt, 1989; Woodward-Clyde Consultants, 1983) involving different depths and sizes of borehole and a variety of waste container geometries, materials and contents. Essentially, these fall into two main categories that can be referred to as 'high temperature' and 'low temperature' very deep disposal, or DBD (Gibb, 2010; Gibb *et al.*, 2008a). In the former the temperatures generated by radioactive decay of the wastes are high enough to induce partial melting of the host rock around the waste packages (>~700℃). In the latter, temperatures in and around the borehole are well below those required to melt the host rock and are usually below approximately 250℃. For a variety of reasons, including the nature of existing spent nuclear fuel and HLW inventories, current investigations, R&D and interest are focussed on the low-temperature variants.

3. Waste packages

Largely because of the volumes involved, DBD has really only been proposed for spent nuclear fuel, vitrified reprocessing wastes and fissile materials. With the possible exception of plutonium (Gibb *et al.*, 2008a) the waste form is invariably enclosed in a cylindrical metal container, usually mild or stainless steel, to form the waste package. Among the most fundamental parameters for any DBD are the dimensions of the package, its weight and the heat output of its contents. The diameter of the package; that is, the outside diameter (OD) of the container effectively determines the size of the borehole required throughout the disposal zone and hence should be the primary influence on the borehole design. In this section the parameters of some waste packages likely to be required for DBD of spent nuclear fuel, reprocessing HLW and plutonium are considered.

3.1 Spent nuclear fuel

The fuel for nuclear reactors comes in a wide variety of compositions, physical forms, shapes and sizes. For the most common type of fission reactor, the light water reactor (LWR), the fuel element or assembly consists basically of a number of long, thin cylindrical fuel rods held in place within a square metal frame by various grids, spacers and springs (Figure 2). After irradiation in the reactor the fuel rods are highly radioactive, but the other metal components of the assembly are much less so and would be classed as only intermediate-level waste and need not follow the same disposal route as the fuel itself.

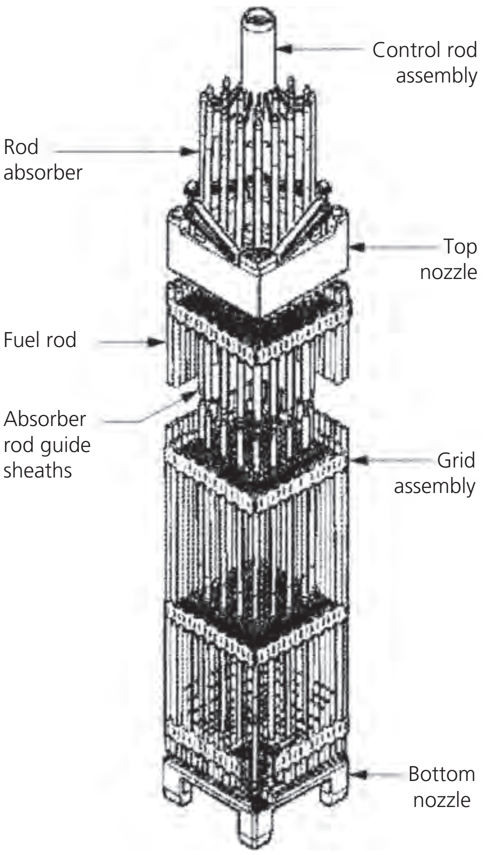

Figure 2. Typical pressurised water reactor fuel assembly (Westinghouse AP 1000 reactor) (from NDA, 2009)

During operation of the reactor, rods can occasionally become damaged and need to be removed or replaced. The assembly is designed so this can be done by remote operation in the reactor fuel pond when the assembly is out of the reactor. The exact procedure varies with the reactor type and assembly design, but this creates a mechanism whereby the spent fuel rods could be separated from the rest of the assembly for storage and/or disposal. This is known as fuel rod consolidation. Perhaps counterintuitively, consolidation lowers even further any risk of criticality in a DBD by reducing the volume within the container that could eventually fill with water (to moderate the reaction).

3.1.1 Disposal of complete LWR assemblies

There are two main types of LWR in operation worldwide – boiling water reactors (BWR) and pressurised water reactors (PWR). A typical fuel assembly for a BWR is 0·139 m square and 4·42 m high, contains around 74 fuel rods and weighs about 300 kg. A cylindrical container to take a single BWR assembly would require an internal diameter (ID) of 0·198 m and internal height of 4·43 m.

For DBD the containers must be sufficiently robust to withstand any damage that might occur during emplacement, an external hydrostatic pressure that could eventually exceed 150 MPa and load stresses from overlying waste packages without losing its integrity, ideally until long after the borehole is sealed. Clearly, the container cannot be expected to withstand the load stresses imposed by the whole (>1 km long) stack of potentially very heavy waste packages and some form of additional support (see Section 7) would be required. For a stainless steel container with a welded lid preliminary calculations suggest that a wall thickness of approximately 2 cm would be needed, giving an OD of 0·238 m, but a detailed analysis of the stresses involved is required as part of the container design R&D. Also, to minimise any risk of collapse under the external pressures, the voids within the container must be filled. The more complete the filling of the voids the greater the reduction in any risk of post-disposal criticality by minimising the space available for the influx of water when eventually the integrity of the container is breached. Materials suggested for filling range from graphite or silica sand (Sapiie and Driscoll, 2009) through bentonite to molten lead (Gibb *et al.*, 2008b, 2012). While molten lead guarantees complete filling of the voids, provides a barrier to the escape of radionuclides, affords radiation protection and has the additional benefit of disposing of irradiated lead from the nuclear industry, it adds significantly to the weight of the package. Depending on the infill, a 0·238 m OD container with one BWR assembly would weigh between 800 and 1900 kg.

A typical PWR fuel assembly (Figure 2) is 0·215 m square and 4·795 m high, contains approximately 264 fuel rods and weighs about 700 kg. The container for a single assembly would require an ID of 0·32 m and an internal height of 4·81 m. Depending on the infill, such a package with an OD of 0·36 m would weigh between 1400 and 5000 kg.

Some DBD schemes have sought to accommodate the disposal of multiple complete fuel assemblies, notably three BWR assemblies (Sapiie and Driscoll, 2009) and four BWR assemblies (Juhlin and Sandstedt, 1989). Three BWR assemblies could be fitted into a container with an ID of 0·365 m (OD of 0·405 m) and inside height of 4·43 m (external height of 4·47 m). Such waste packages would weigh between 2000 and 5650 kg, depending on infill and could be approaching the upper limits of possible borehole diameter. The SKB concept for four BWR assemblies was subsequently deemed to require a borehole diameter in excess of 0·8 m (Harrison, 2000) and is probably outside the envelope of what could be achieved at this stage without significant technological development (Beswick, 2008). Direct disposal of complete assemblies is likely to be favoured by waste owners as it avoids dismantling of the assemblies in the fuel ponds with its additional costs and a slight extra risk of radiation exposure to the workforce. The downside is that it is very wasteful of borehole disposal space and significantly increases the cost of DBD compared to the disposal of consolidated fuel rods.

3.1.2 Disposal of consolidated fuel rods

Fuel rod consolidation aims to dispose of as much spent fuel as possible in each container. Containers for the disposal of fuel rods would not need to be quite as high as those for complete assemblies. For example, PWR fuel rods are only 4·58 m long so the container need be only 4·6 m high compared to 4·81 m (internal). However, if containers already existed for the disposal of complete assemblies it would make sense to use these for the fuel rods as well. Taking a single PWR assembly container with an ID of 0·32 m (OD of 0·36 m), the maximum theoretical number of PWR fuel rods it could hold would be 1029. However, given that the rods would have to be inserted remotely into the containers, maximum packing densities are unlikely to be achievable in practice and a more realistic figure is likely to be around 80% or 825 rods (Gibb *et al.*, 2012), equivalent to just over three PWR assemblies. Again, the voids between the rods would have to be filled and, depending on the material used, a 0·36 m OD steel container with 825 PWR fuel rods would weigh between 3200 and 4300 kg.

Containers capable of taking three BWR assemblies (ID of 0·365 m, OD of 0·405 m) could hold up to 1338 PWR rods with a practical number around 1071 or the equivalent of four PWR assemblies. Such waste packages would weigh between 4000 and 5400 kg depending on infill.

3.2 Vitrified reprocessing HLW

Reprocessing of spent nuclear fuel with vitrification of the waste products has taken place in some countries, notably France, the UK, the USA and Russia. The vitrified HLW produced at Sellafield (UK) and La Hague (France) is packaged in cylindrical stainless steel containers 0·43 m OD and 1·35 m high with a wall thickness of 0·005 m, each containing 380–390 kg of vitrified waste. It has been suggested that these packages could be suitable for DBD without overpacks, but with such thin walls it may be debatable whether they could withstand the stresses involved. In designing a DBD for these wastes it would be prudent to allow for an overpack with a wall thickness of at least 1 cm, giving a package OD of 0·45 m and overall height of 1·37 m.

The reprocessing waste produced at Hanford (USA) is in much larger packages with a diameter of 0·61 m and a height of

4·57 m. It seems unlikely that DBD could accommodate such packages, at least until larger holes can be drilled.

3.3 Plutonium

Plutonium is a strategic material and to date no country has declared it as waste, although a case can be made on security and non-proliferation grounds for disposal (Von Hippel *et al.*, 2012). Plutonium can be burned in LWRs as mixed oxide fuel (MOX) and some countries (e.g. France) already do so while others such as the UK, which has the world's largest stockpile of civil plutonium, the USA and Russia have indicated an intention to do so. The spent MOX fuel would then be disposed of like other spent LWR fuels, and Gibb *et al.* (2012) have demonstrated that DBD would be well suited to MOX disposal.

Direct disposal schemes for plutonium usually involve its immobilisation in some form of ceramic (Ewing, 1999), low specification MOX (i.e. MOX not intended for use in a reactor) or recrystallised rock (Gibb *et al.*, 2008a). However, it can also be put into small packages inserted into larger containers of spent fuel or HLW – the so-called 'can-in-can' method (Kuehn *et al.*, 1997). As no plutonium has yet been packaged for disposal, there are few constraints on the size of any containers used, although criticality issues could favour quite small packages. Given the relatively small volumes involved, the best strategy for DBD of plutonium would undoubtedly be small-diameter packages requiring only modest borehole diameters, thus enabling greater disposal zone depths than for spent fuel or HLW if desired.

3.4 Container ODs

It is clear from the above that for the DBD of spent nuclear fuel borehole sizes and designs need to be capable of accommodating packages with an OD of at least 0·36 m (one PWR assembly) and ideally 0·405 m (three BWR assemblies). If already packaged vitrified reprocessing wastes (other than Hanford packages) are to be disposed of, a package with an OD of 0·45 m needs to be accommodated. Consequently, throughout the remainder of this paper the assumption is made that the target diameter for the boreholes should be 0·61 m (24 in) or 0·66 m (26 in). These are the two standard diameters that could take the size of casing needed for a 0·45 m package with adequate and preferable clearances, respectively.

4. Deep borehole construction

Over the 50 years since DBD was first considered, there has been continuous and comprehensive development in all aspects of deep borehole construction driven by the demands of the oil and gas industry to find new resources, geothermal development requirements and also for deep and very deep geoscientific boreholes. Since reviews in the 1980s (e.g. Juhlin and Sandstedt (1989) and more recently Beswick (2008)) improvements in drilling technology and equipment and a better understanding of geomechanics in deep stressed rock have continued. Beswick (2008) gives some examples of drilling achievements up to that time.

Consideration of drilling for DBD to date has been based on desk studies drawing experience from the traditional deep drilling industries, such as the hydrocarbon, the geothermal energy and the mining industries, and from geoscience projects with the conclusions largely influenced by what has been achieved to date and translating it into a possible scenario for DBD. This understandable, but conservative, approach has not considered what could be achieved if there was a need to drill larger diameter boreholes to depth.

In future considerations of DBD as an option for certain wastes, the borehole size should be governed by the sizes of waste packages required to optimise the potential application of DBD. From the discussion above (Sections 3.1 to 3.4) it would appear that a 0·445 m (17·5 in) diameter clear hole (i.e. inside casing) size would accommodate a large proportion of the spent nuclear fuel inventory and a 0·50 m (19·7 in) clear hole could take all but the largest reprocessing waste packages. A 0·445 m clear hole is a convenient size as it corresponds to a standard size for deep drilling equipment used in the oil industry, but necessitates a nominal hole diameter of not less than 0·610 m to accommodate the size of steel casing that would need to be installed through the disposal zone. This is not a size that has been drilled to date at the 4000–5000 m depth in any of the supporting drilling industries, and larger diameters would be necessary in the upper parts of the borehole to provide support by casing the borehole in stages, the depths of which are governed by the geology.

In a report to the UK Nuclear Decommissioning Authority, Beswick (2008), presented a historical summary of depth against diameters in graphical form and, based on previous experience, concluded that a 0·30 m hole size and even a 0·50 m hole size were probably achievable extensions of hole diameter at 4000 m. Noteworthy is that significant 'big hole' experience was gained from drilling for military purposes. The US government drilled 550 large-diameter boreholes to depths of 1000 m or more with diameters from 1·22 to 3·66 m and opened some to 6·4 m diameter for nuclear munitions testing. Similar programmes were also undertaken in large-diameter boreholes in the former USSR, China and by the French in the Pacific Islands (Beswick, 2008; FAS, 2007).

The idea of drilling a 0·61 or 0·66 m diameter borehole to a depth of between 4000 and 5000 m, while challenging, is certainly not out of the question. Thirty years ago in 1983 and 1984, a 3810 m deep hole was drilled and a string of 0·508 m (20 in) casing installed in the 0·66 m diameter hole to a depth of 3800 m in Louisiana, with an internal drift diameter of 0·462 m (Pejac and Fontenot, 1988). This paper summarises the casing design processes and quality assurance for deep large-diameter strings and is as relevant today as it was then. At the time, this was an impressive achievement and highlights the fact that the DBD concept requires only a modest advance on what was achieved almost 30 years ago.

In recent years, the focus of deep drilling has been on ‘long reach’, horizontal drilling and deep ocean drilling, and not so much on large-diameter wells to great depths. Development in drilling technology is driven by demand. For example, in the early 1980s, less than 1% of all drilling in the USA was carried out using down-hole drilling motors rather than surface rotation of the drill string (Beswick and Forrest, 1982). A conservative approach at that time would never have contemplated the massive changes that have occurred in directional drilling equipment and practices using these down-hole devices enabling long reach wells in the oil industry to reach lengths of more than 12 km, with horizontal sections of over 11 km on Sakhalin Island, Russia (Exxon Neftegas, 2013). The shale gas revolution in the USA with over 25 000 or more wells drilled each year, together with other shale gas developments worldwide, routinely drills lateral sections up to 1500 m long, a practice that would not have been thought possible 10 years ago. These examples highlight how those who pioneer new applications outside the conventional envelope of current practice can achieve results that conservative minds would not contemplate. DBD is at this stage and needs some bold thinking and investment to explore this option fully for radioactive waste.

Compared with the billions of dollars spent worldwide in the pursuit of relatively shallow mined repositories, investment in DBD to date has been minimal. Therefore, it is not reasonable to dismiss the scenario that, in favourable geology, a deep vertical borehole can be drilled to between 4000 and 5000 m with a final hole diameter of 0·61 m or more and with a clear cased hole diameter of 0·445 m or over. To advance the DBD concept a full-scale trial borehole that would prove feasibility, is essential. The trial borehole would also enable development of the drilling equipment and practices, testing of the deployment methods with dummy waste canisters and investigation of sealing options. Individual elements of the processes involved could also be tested in shallow boreholes, for example, in a quarry, such that the outcomes could be verified by inspection after exposure by excavation.

Demonstrating the concept of DBD would be a major project requiring heavy equipment (Figure 3), comprehensive borehole design work, equipment engineering and planning with meticulous attention to detail, but it offers huge rewards in the form of a safe, feasible and economic option for nuclear waste disposal. Most of the elements for the design and construction of deep, large-diameter boreholes are already in place, but for those that are not, or require development or adaptation, each is a significant challenge in its own right. Some key aspects and the status of the related technologies are summarised below.

4.1 Geological setting

Much of the continental crust is underlain at suitable depths for DBD by granitic basement rocks. Experience over the past 40 years in geoscientific and geothermal energy boreholes provides considerable data on drilling in granitic basement rocks. While very different from the geological conditions generally encountered in the oil and gas industry, this allows a detailed design to be undertaken with confidence. From a drilling perspective, site selection ideally should avoid complex sedimentary sequences that necessitate several intermediate casing strings, but any sedimentary cover should be easy to drill and relatively stable. Selection should also provide a stable formation throughout the proposed disposal zone. Boreholes should be sited to avoid abnormally geopressurised zones, potential hydrocarbon provinces, mineral resources (as indicated by surface and known expressions of economic mineralisation), likely geothermal energy prospects (high geothermal gradients) and other sub-surface resources likely to attract

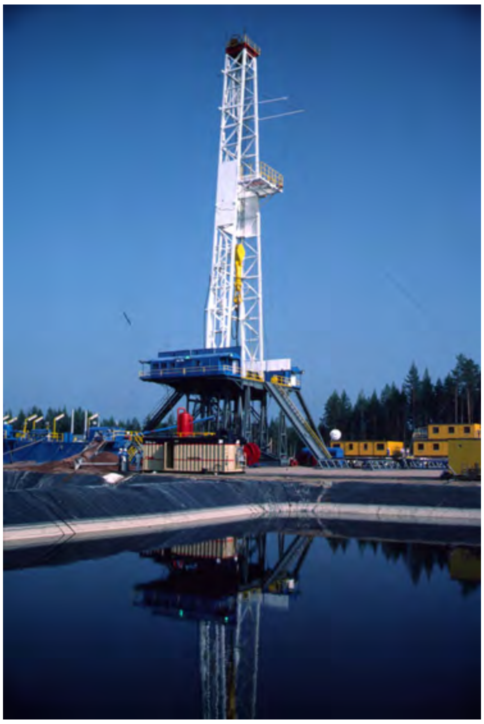

Figure 3. Heavy drilling rig suitable for deep borehole disposal

attention in the future and hence liable to intrusion. Regions where significant anisotropic horizontal stress differences occur should also be avoided.

4.2 Exploratory boreholes

Before the design and construction of any borehole or clusters of boreholes for DBD, a slim exploration borehole should be drilled to slightly beyond full depth to determine the geology, hydrogeology (especially hydraulic conductivities and hydrogeochemistries), pressure and stress conditions at the chosen location through mud logging, geophysical logging and other appropriate testing. Such a borehole poses no special challenges as several similar boreholes have been drilled successfully before and some much deeper than the planned depth of a DBD hole. Noteworthy, however, is the need to seal any exploratory borehole after completion of the evaluation programme in the same way that an actual DBD hole would be sealed, otherwise the borehole may provide a conduit for the eventual release of radionuclides to the biosphere.

4.3 Borehole design

First, a scheme for the intermediate and final casing depths and diameters must be determined. The exploration borehole would provide important data to assess the necessity for borehole wall support or the isolation of certain geological strata for a variety of reasons. One of the principal tasks is to design and analyse the stresses in the various casing strings for all loading conditions during the construction of the borehole, waste package deployment and sealing phases. The current practice for complex and exotic wells and those wells that experience stress cycling, such as for gas storage and engineered geothermal systems, is to adopt a design approach using a computer model developed over 25 years ago (Jellison and Klementich, 1990) and enhanced in recent years. This and other similar tools are technically robust tubular design and analysis models that consider all loading conditions of the casing and the von Mises equivalent stress-intensity criteria. Borehole design also addresses all aspects of the borehole construction including the drilling fluids programme and provides a road map for the execution of the drilling phase of the project.

Noteworthy is that the actual drilling, casing and cementing of the borehole, other than the verification of the integrity of the final casing string that would be installed to the bottom of the borehole is effectively ‘temporary work’ as against the waste package deployment and disposal zone seals (see Sections 5, 7 and 8), which are effectively the ‘permanent works’. During construction of the temporary works, and even to the point that the final casing is installed, the risk of problems and even failure inherent in deep drilling presents no danger and the borehole could be remediated or even abandoned at any time. The essential guarantee that has to be achieved in constructing the borehole is that once the final casing is in place, access throughout the borehole for waste deployment must be guaranteed. At this point the status of the ‘facility’ changes to a nuclear waste disposal facility.

4.4 Surface drilling and associated equipment

There is already in existence a small number of heavy land drilling rigs with the necessary capacity to construct a deep, large-diameter borehole for DBD (Figure 3). These have a lifting capacity of 1000–1200 t that would be adequate for the heaviest loads, which will be the casing loads during installation. All other supporting surface equipment is readily available.

In practice, if DBD were adopted as a method for the disposal of radioactive waste, it is envisaged that a purpose-designed rig would be constructed specifically for the drilling. Drilling rigs currently incorporate a high level of mechanisation and, to some degree, automation. The process of the development of more sophisticated and automated drilling rigs is a current issue in the oil and gas industry with increasing focus on safety by eliminating risks to personnel with various initiatives already in hand to develop a ‘drilling factory’ (Mazerov, 2011).

4.5 Hole advancement methods

Hole construction in these deep, large-diameter boreholes would require a blend of blind shaft drilling and oilfield drilling. For the upper large-diameter section, a reverse circulation approach is probably appropriate and this is the normal practice for shaft drilling. Combination roller bits or plate bits in various formats are available or can be manufactured for different geological formations. In the crystalline granitic basement, which would be drilled largely in 0·61 m (24 in) or 0·66 m (26 in) diameter, standard tungsten carbide insert bits are applicable with normal circulation, as used for most previous drilling in granite for geoscientific and geothermal energy applications. As well as rotary drilling, the use of hammer drills with drilling fluid circulation may be possible to increase the speed of drilling in the harder formations. Such devices are becoming available and can be engineered for hole sizes up to 0·66 m and even larger (M. McInnes, 2013, personal communication). The use of cluster configurations for the larger diameter hole sections may also be appropriate.

Extra-large drill pipe is already manufactured in 0·194 m (7·63 in) size and drill collars in 0·305 m (12 in) and 0·356 m (14 in) sizes for drilling the lowermost intervals. Oilfield drilling is normally carried out with 0·127 m (5 in) drill pipe and 0·15 m (6 in) to 0·24 m (9·5 in) drill collars. For the large diameters needed in the uppermost intervals of the borehole, the shaft drilling industry routinely utilises ‘donut’ drill collars with plate or multi-roller bits.

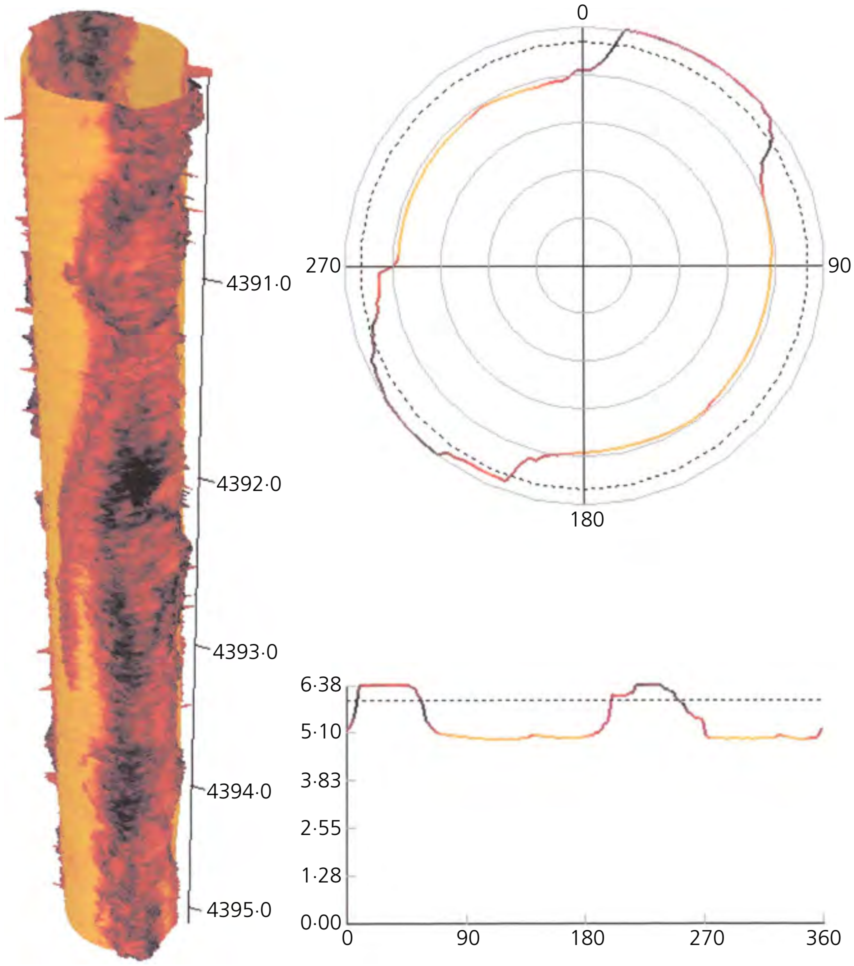

Figure 4. Illustration of stress breakout in deep boreholes (depth in metres, radius in inches) (from Beswick, 2008)

Progress rates for drilling in the basement are well understood. For example, the progress rate during drilling in the basement from 2400 to 5000 m in the Basel geothermal well drilled in 2006 (Häring *et al.*, 2008) was achieved at a rate almost identical to the prediction of approximately 40 m a day.

4.6 Deviation control

Drilling deep vertical boreholes necessitates careful control of verticality. Large-diameter holes, in particular, also require tortuosity to be minimal to allow stiff casing strings to be installed. An automated vertical drilling system was developed as part of the Kontinental Teifbohrprogram project in Germany, where a deep geoscientific borehole was drilled to a depth of 9001 m between 1990 and 1994. The vertical drilling system was used to 7500 m and controlled the verticality to within a departure of 12 m in 7500 m (Emmermann and Lauterjung, 1997; Engesar, 1996). These tools have since been further developed to become a robust workhorse for directional and vertical drilling in the oil industry (Ligrone *et al.*, 1996) and are available up to 0·66 m hole size.

Tortuosity can be overcome by drilling with stiff bottom hole assemblies and reaming to ensure that the hole is straight. Some advancement methods can create a spiral effect and this must be avoided by the application of the appropriate tools and drilling practices.

4.7 Geomechanics issues

Borehole stability is largely controlled by the in-situ stress regime arising from the tectonic history and the mechanical properties of the rock through which the borehole is drilled. Geomechanics considerations are now a mature element particularly in deep and exotic well design, and many models have been developed to investigate the effects (Cook *et al.*, 2007; Grandi *et al.*, 2002). Anisotropic horizontal stress differences lead to borehole breakout or elongation of the borehole shape. As an example, in the Basel geothermal well drilled to 5000 m (Beswick, 2008) the drilled diameter was 0·251 m, but the dimension on the long axis in parts was 0·430 m (Figure 4). However, even with an open hole section from 2400 to 5000 m, the well was relatively stable for some time. The borehole was suspended in 2008 and re-entered in 2010 when there was some restriction at 4673 m while trying to reach the bottom with coiled tubing (see Section 5.2.4) (M.O. Håring, 2013, personal communication). Breakout and hole elongation can in part be controlled by the properties of the drilling fluid, but nevertheless is a concern in all deep wells. In the case of DBD in which the proposed diameter is larger than is normally drilled at the depth of interest, the geomechanics issues need thorough investigation. Data from a slim exploration borehole in a potential location for DBD should provide the necessary information on the state of stress to allow a geomechanics model to be developed.

4.8 Casing

The borehole design will determine the borehole configuration and the appropriate sizes and properties with the depth of the nesting casing that needs to be installed to provide effective support. While any borehole design has to be related to geology and borehole stability factors, a typical scenario could be as shown in Table 1. This scenario is shown in Figure 5 overlain on some of the historical examples of actual depths and diameters achieved (Beswick, 2008).

The two uppermost casings would have welded connections as for shafts and water wells. The 0·762 m (30 in) casing could have screwed connections. This is a standard oilfield size and casing is readily available. The borehole must be cased to the bottom with no open hole to guarantee waste package deployment without any problems. The lowermost casing (0·508 m) would be perforated in the disposal zone to facilitate the waste package support and sealing programme (see Section 7). This casing is also readily available as a standard oilfield product and the string could be welded using the latest in-situ welding process (TubeFuse, 2013). This would also remove any risk of 'hang up' on upset casing connections during installation. Moreover, most casing failures occur at screwed connections and a welded string would remove this risk during the service life of the casing.

Depth: m	Hole diameter: m (in)	Casing OD: m (in)
Surface to 50	1·524 (60)	1·372 (54)
50 to 1000	1·220 (48)	1·016 (40)
1000 to 2500	0·914 (36)	0·762 (30)
2500 to 5000	0·610 or 0·660 (24 or 26)	0·508 (20)

Table 1. Typical borehole design and casing sizes for deep borehole disposal

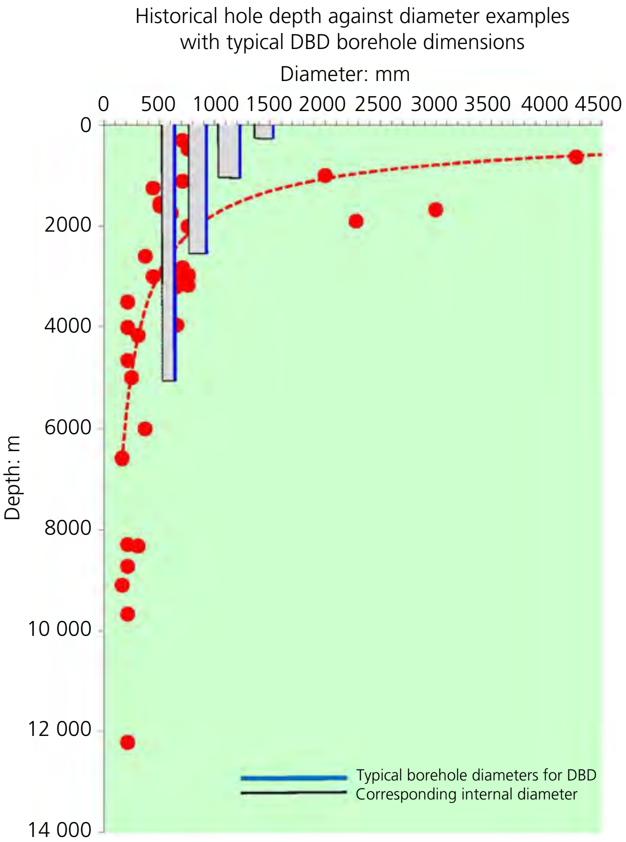

Figure 5. Depth against diameter for previous deep drilling projects with superimposed typical deep borehole disposal (DBD) borehole dimensions (after Beswick, 2008)

4.9 Cementing

Cementing of casing is necessary for casing stability and isolation of any intervals from a drilling perspective. Traditional oilfield cementing practices and verification do need some examination to determine where improvements can be made. An example of cementing a 3800 m string of 0·508 m casing was reported in a well in Louisiana in 1984 (Pejac and Fontenot, 1998). The proposed sealing process to isolate the disposal zone (see Section 8.2) will create containment within the host rock itself at depth. Once the waste has been emplaced, this sealing has to be implemented through windows cut in the 0·508 m casing to allow direct access to the host rock. However, window cutting in casing is a standard procedure in the oil industry.

4.10 R&D topics

While many of the elements of the borehole construction for a DBD solution to radioactive waste disposal are already available, there are some topics that need development, adaptation or further research (Beswick, 2008). The R&D programme should begin with a status review of the applicable technologies as some of the key topics have already advanced since the previous reviews through other initiatives. In particular, uncertainties remain in relation to the geomechanics in large-diameter boreholes at depth, casing design and installation in such large diameters, some large drilling tool design details and the sealing and cementing issues (see below).

Two related aspects crucial to the success of DBD are the development of sealing and support matrices (SSM) for the waste packages and a technology for sealing the borehole above the disposal zone in order to prevent it becoming a route for the escape of radionuclides to the biosphere (see Sections 7 and 8). Conventional materials and methods for sealing oil, gas and geothermal energy wells are unlikely to prove satisfactory for DBD of radioactive wastes and the associated long-term safety cases required. Consequently, research is required into both waste package SSMs and methods for sealing the borehole itself, and such programmes, in which the authors are involved, are underway at the University of Sheffield with the former funded by the Engineering and Physical Sciences Research Council.

5. Deployment strategies and methods

Strategies for waste package deployment will depend on many things, such as the number, weight and heat output of the packages, the emplacement mechanism employed and the capacity of the rig. The factors governing the rate at which the packages can be deployed in DBD however are

- the rate at which packages can be delivered to the site and readied for emplacement, and
- the time required to deliver the packages down-hole to the disposal zone, recover the delivery equipment and ready it for the next emplacement (i.e. the round trip time).

For various operational and economic reasons, DBD requires that the packages can be deployed at rates of the order of one per day. Most DBD concepts assume that waste packages would be deployed singly. However, it has been suggested that they could be deployed in small batches with physical and/or temporal separation between batches (Gibb *et al.*, 2008a) or even in 200 m-long strings of up to 40 packages (Arnold *et al.*, 2011). The deployment mechanism is usually taken to be lowering on the end of the drill pipe using the drilling rig or a lighter ‘emplacement’ rig. Potentially more efficient methods such as wireline and coiled tubing have been suggested (Beswick, 2008) and are discussed in Section 5.2.

5.1 Deployment rates

For practical reasons waste packages cannot be pushed down the borehole and must be lowered to the disposal zone under tension. There is therefore an upper limit to the speed at which they can be lowered equal to that at which they would free fall under the influence of gravity alone. This limiting velocity is also important in the context of the accidental release of a package during emplacement and the operational safety case.

The sinking of a cylindrical package in a fluid-filled borehole is complicated by the ‘piston’ or ‘hydrodynamic braking’ effect, which becomes increasingly more important as the clearance between the package and the casing decreases. Laboratory-scale experiments indicate that, while clearance is the dominant factor, there is also a relationship between the mass of the package and the limiting sinking velocity. The clearance between the waste package and the casing should be as small as possible to minimise the size and cost of the borehole if waste package diameter is the controlling factor or to maximise the amount of waste that can be disposed of if borehole diameter is a constraint. On the other hand, the clearance must be sufficient to eliminate any risk of jamming or damage to the container during the descent to the disposal zone. Clearances of 0·02 or 0·03 m have been suggested (Arnold *et al.*, 2011; Gibb *et al.*, 2012), but the optimum clearance needed to guarantee fail-safe package emplacement can only be ascertained by trials in a full-scale borehole.

Depending on their size, construction and contents, waste packages for the DBD of spent nuclear fuel are likely to weigh between 800 and 5650 kg (see Section 3.1) and preliminary calculations suggest the limiting sinking velocity in a DBD with a container OD to casing ID ratio of 0·85 (Arnold *et al.*, 2011; Gibb *et al.*, 2012) would be between 0·5 and 2·0 m/s. It is therefore likely to prove impossible to lower waste packages to the disposal zone of a 4–5 km deep borehole in under an hour. However, in practice the limiting factor on the time taken to reach the disposal zone will almost certainly be the emplacement mechanism.

5.2 Emplacement mechanisms

The emplacement of the waste packages, whether individually or in strings, must not be affected by any tortuosity in the borehole, but with the diameter, well construction and casing methods proposed, this should not be an issue. However, before any emplacement, the borehole would be checked thoroughly by running a calliper and/or a dummy waste package. Four main mechanisms could be considered

- free fall
- wireline
- drill pipe
- coiled tubing.

5.2.1 Free fall

'Free fall' should be considered only as a theoretical possibility for deployment, but it is important in the context of a waste package becoming detached from the equipment in other deployment methods. In the latter event the terminal velocities appear unlikely to result in any significant damage to robust steel containers. It is not an uncommon means of down-hole delivery in drilling operations and is the standard method when using wireline core barrels whereby the inner barrel is replaced by free fall to latch into the outer barrel on each sampling trip. Descent rates depend on a number of factors including the borehole fluid viscosity, package mass and the clearance (see Section 5.1). However, free fall allows no control on the emplacement and should not be employed for DBD of radioactive wastes.

5.2.2 Wireline

Wireline has the attraction of simplicity, but would limit the weight of the package and provides less control than using drill pipe or coiled tubing. It also carries an increased risk of 'hang ups' leading to recovery problems inappropriate for the disposal of radioactive wastes. There are two types of line – 'slick line' and 'wireline with electrical conductors'. The former is just a braided wire line in various sizes with depth control measured from the surface. A wireline with electrical conductors allows a release mechanism to be triggered and transmission of monitoring data, such as depth control by reference to fixed points in the casing string. All forms of wireline stretch much more under load than metal tube so depth control by reference to casing collars or markers recorded during installation is essential. Wireline winch systems can deliver up to 6000 m/h, but the actual package emplacement speed will depend on other factors such as the limiting velocity and is likely to be much less. Units are available with combined hydraulic cranes enabling a relatively small set-up over the borehole.

5.2.3 Drill pipe

The traditional means of working within a borehole, this requires a drilling or 'workover' rig and a relatively large site area. Drill pipe comes in 9·45 m or 12 m standard lengths and various diameters and steel strengths. Deployment is discontinuous in that each length of pipe has to be added or removed with each connection screwed in or out of the next. The rigs include various devices for making up, breaking out and torquing the drill pipe to the correct values. Deployment speed depends on the height of the rig and whether it is manual or automatic. Traditional 'triples' rigs lower or pull three lengths of 9·45 m drill pipe (i.e. ~28 m) at a time and rack the pipe stands back in the mast or derrick. The smaller 'doubles' variants pull two lengths of pipe (~19 m) and the rigs known as 'super-singles' handle one length of 12 m pipe. With conventional rigs this process requires a 'derrick hand' working high in the mast to rack the pipe back into finger boards designed to accommodate the size of pipe being used. However, modern rig designs, driven by health and safety concerns, have eliminated this practice through the use of robotics, with various types of pipe handling devices being available. Deployment speeds (or 'trip speeds') range from 500 to 600 m/h for automated systems to typically 1000 m/h in a cased hole with an experienced driller and derrick hand team, who must work efficiently together to enable such fast tripping. For DBD an automatic system would be preferable on safety grounds, and modern rigs are becoming increasingly sophisticated with the elimination of most of the manual operations. Using drill pipe the waste package release mechanism would have to be mechanical, which introduces some uncertainty, but a suitable system could be engineered. Depth control would be through the normal practice of surface measurement as the drill pipe is run.

5.2.4 Coiled tubing

The development of coiled tubing systems (Figure 6) has been rapid in recent years and they are now used for drilling, well intervention, logging and well completion operations, with a wide range of equipment available (Afghoul *et al.*, 2004; ICTA, 2005). New systems incorporate electrical conductors through the continuous tube allowing data transmission and commands for release mechanisms. The equipment is widely used in

Figure 6. Coiled tubing unit

different sizes and to depths well in excess of the 4–5 km proposed for DBD and with load capacities in excess of what would be necessary for waste package disposal. Deployment speeds could be 2000–3000 m/h with a waste package release mechanism triggered by means of conductors in the tubing and data acquisition possible through others. The surface set-up would be relatively small so reducing environmental disruption and significantly more cost effective than maintaining a drilling rig on site.

5.3 Emplacement times

The 'round trip' for waste packages, emplaced by whatever method, is not simply a matter of down-hole and return travel times (Schlumberger, 2013). It must also allow for surface operations – like attaching the package(s) – depth checks, package release and any other procedures that have to be undertaken in the disposal zone (see Section 7). Conservative estimates of the time required for a single emplacement trip using each of the three possible methods are

- wireline 8 h
- drill pipe 18 h
- coiled tube 8 h.

These times for wireline and coiled tube emplacement offer scope for improvement with practice, but at some increased risk, especially for the former in which fast running can lead to entanglements. Emplacement of very long and heavy strings of waste packages would probably necessitate the use of drill pipe, but the advantages of coiled tube could warrant reconsideration of this strategy towards individual emplacement or much smaller strings.

The basic equipment and systems for all three options are readily available, although some development of bespoke items such as waste package release mechanisms would be necessary. However, development costs would be minimal. In selecting the emplacement mechanism for the DBD of radioactive waste packages consideration needs to be given to the mechanisms and equipment that reduce to a minimum any risk of exposure to people at and around the site. Although every effort should be made to employ mechanisms that minimise the risk of accidental release of the packages this is, contrary to common misconception, not a serious problem. The terminal velocities reached in free fall of a waste package (see Section 5.1) are unlikely to result in any significant damage to a steel container. It is apparent from the above summary that the coiled tubing method would be the preferred option, with the additional benefit of being much more cost effective than the use of drill pipe necessitating a drilling or workover rig. Ideally, the waste disposal organisation would own a purpose-designed equipment package so the cost spread over a substantial disposal programme would be relatively low. However, for a demonstration borehole or pilot scheme, it would be preferable to utilise equipment readily available in the drilling industry.

6. Heat flow

Almost all the HLW appropriate for DBD generate significant amounts of decay heat, which, although transient on timescales of hundreds to thousands of years, add to the ambient temperatures at disposal zone depths. From various materials performance and engineering perspectives it is important to be able to predict the spatial and temporal distribution of temperature in and around the borehole and this is done by modelling heat flow for specific disposal scenarios. To a good approximation, the spatial and temporal distribution of temperature for a single borehole with emplaced waste can be treated as two separate problems in heat conduction and convection, with the former the dominant form of heat transfer. The solution from the conduction model can then be used as input to determine the extent of any convection.

The solution of the heat conduction equation of continuum mechanics is most easily obtained through the finite difference method (FDM), which transforms the partial differential equation into a sparse system of linear algebraic equations yielding solutions for the temperature at the nodes of a Eulerian grid, superimposed on the problem space. DBD heat flow research at the University of Sheffield utilises a dedicated heat conduction code, 'Granite' (Gibb *et al.*, 2008b, 2012; Travis *et al.*, 2012), which employs the FDM to model disposal of one or more containers in a single borehole. This code uses variable mesh spacing, with finer resolution in and near the borehole, and a coarser mesh in the far field. Components such as the casing, SSM (see Section 7), container material, container infill and waste are included in the model by assigning relevant material properties (density, specific heat and thermal conductivity) to the mesh points within the appropriate spatial regions. The temperature dependence of these properties is built in to the code.

The source term is an essential aspect of any heat flow model. In 'Granite' it is represented by those mesh points that lie within the waste region. In the case of DBD of consolidated fuel rods (see Section 3.1.2) the 'waste' consists of the fuel rods and their infill but only the central sections of the rods generate heat and this is accommodated in the model. A nuclear industry standard code, FISPIN (Burstall, 1979), is used to obtain decay curves for the particular spent nuclear fuel or waste. Where the 'waste' region is composite (e.g. comprising the fuel rods, their cladding and the infill) the thermal conductivity, density and specific heat of the composite material is estimated using models that treat the problem as thermal resistors in series and parallel arrangements. Another key feature of our FDM modelling is the inclusion of latent heat. Latent heat is less important in ‘low temperature’ DBD schemes than ‘high temperature’ versions, but it is significant for modelling rock welding scenarios (see Section 8.2 and Figure 7). In such cases, in which the heat melts the granite, subsequent cooling also needs to take account of the latent heat of crystallisation.

With an FDM code such as ‘Granite’, it is a straightforward task to determine temperature–time curves for any point in or around the borehole. These can be used to create peak temperature isotherm diagrams, which, in the context of ‘high temperature’ DBD or rock welding (see Section 8.2), can be combined with experimental data on granite to predict the size and shape of the melt zone around the waste containers or heater. This modelling also yields data on the times needed before the rock recrystallises and provides guidance on the minimum spacing required between boreholes for multiple borehole arrays and on deployment strategy, for example, waste package contents, batch sizes, emplacement intervals and so on.

Convection in the host rock fluid (groundwater) is treated as a fluid dynamics problem, decoupled from conduction, and solved to determine how far a particle might travel in the upward vertical direction as a result of convective flow in a thermal gradient. This gradient arises from the pre-existing geothermal gradient modified by the decaying heat profile from the stack of waste packages as determined by the conductive modelling. A simple model using a point source of heat permits an analytical solution and a conservative upper bound (Gibb *et al.*, 2008b). Preliminary calculations suggest that this method of potential radionuclide transport is both transient (lasting only a few hundred years) and of minor vertical extent (less than a few hundred metres) with the low hydraulic conductivities anticipated, and hence presents no real threat to containment in the context of DBD.

Heat flow issues are well understood and the modelling is sufficiently advanced to give confidence in the viability of the DBD concept, including the feasibility of sealing the borehole by rock welding. Further R&D in this area should focus on ever more detailed and specific disposal and sealing scenarios with concomitant refinement of the models and codes.

7. Sealing and support matrices

The long-term safety case of the DBD concept does not require the integrity of the containers to survive beyond the emplacement of the main borehole seals above the uppermost waste package (Arnold *et al.*, 2013; Gibb *et al.*, 2012) – at most a few years after emplacement of the packages is completed. However, it would benefit the post-operational safety case to prolong this containment far into the future by protecting the containers from saline groundwater for as long as possible. This could be achieved by inserting an impermeable material into the annulus between the container and the casing and, ideally, into the gaps between the casing and the rock. Depending on the material used, it could also serve as a barrier to the escape of any radionuclides that eventually leach out of the package by impeding fluid flow, sorption and so on.

While the primary function of the barrier material is to prevent the access of groundwater to the container and hence substantially delay corrosion, it has an important secondary function to support the waste packages physically. This will almost certainly be necessary to prevent buckling and other forms of load damage to the container caused by the overlying column of potentially very heavy waste packages. Steel containers could be designed with sufficient wall thickness to withstand these load stresses but at a cost and with a loss of disposal space. Using a support matrix with a high compressive strength would eliminate the need for this and/or the use of other means of reducing the load, such as bridge plugs at intervals up the disposal zone.

Several materials have been suggested for providing either the sealing or support functions for the waste packages, but the ideal is a dual-purpose SSM. Irrespective of the SSM used, a key factor is the need for the waste packages to be centred and aligned within the disposal zone casing. This is necessary to ensure a uniform thickness of seal around the package, and any eccentricity or misalignment would increase the likelihood of container buckling or other damage. Achieving centred alignment is a challenge that must be addressed by the emplacement technology R&D, but numerous solutions seem possible such as centring rollers or fins on the containers.

7.1 High-density matrices

A novel high-density support matrix (HDSM) was proposed by Gibb *et al.* (2008c) for wastes that generate temperatures greater than approximately 185°C in the annulus between the package and the borehole wall. Such temperatures are likely to be less than 150°C above the ambient value (80–130°C) at the disposal depths in continental crust. Suitable packages could contain large numbers of used fuel rods, high burn-up fuel, relatively young used fuel or any combination of these (Gibb *et al.*, 2012). Also suitable could be packages of vitrified reprocessing HLW with high waste loadings or that had not undergone several decades of cooling.

The HDSM is a lead-based alloy in the form of fine shot that is delivered down the drill pipe or deployment tube after the emplacement of each waste package, or small batch of packages. The heavy, free-flowing shot runs into all the spaces around the packages and, by means of weight-reducing perforations in the uncemented disposal zone casing, into any gaps between the casing and wall rock. Within a period of weeks to months (Gibb *et al.*, 2008c, 2012) the decay heat from the waste will cause the temperature to exceed the solidus of the alloy (~185℃), which melts to a dense liquid that fills any remaining voids between the containers and the borehole wall. Over a period of years to decades the heat output of the waste will decline and the alloy will re-solidify, effectively 'soldering' the packages into the borehole.

Although lead alloy HDSMs, which could have the added benefit of disposing of contaminated lead from the nuclear industry, work on a laboratory scale, they have yet to be tested in a full-scale borehole. This is something that could be done simply and economically using a shallow borehole, for example, in a quarry (see Section 4). For waste packages not capable of generating the moderate temperatures required for an alloy HDSM an alternative 'low temperature' SSM is needed. This could apply to a significant part of the inventory of older spent nuclear fuel, especially if fuel rod consolidation is not used.

7.2 Cementitious matrices

Many mined repository concepts, such as SKB's KBS-3, employ a layer of bentonite as the primary barrier around containers of spent nuclear fuel and some DBD concepts (e.g. Arnold *et al.*, 2011; Juhlin and Sandstedt, 1989) have suggested a similar material might be used to fill the annulus between the waste packages and casing. The successful use of swelling clays such as bentonite depends on inserting it dry and compacted into a confined space so subsequent hydration causes it to swell and create an impermeable barrier to groundwater. In a mined repository situation this is usually attempted by using shaped, pre-compacted blocks, but this is difficult and it would be virtually impossible to emplace dry bentonite around the waste packages at the bottom of a water-filled borehole. Consequently, if bentonite were to be used to surround and support the waste packages in DBD (e.g. Arnold *et al.*, 2011) it could only be as an uncompacted slurry. Moreover, there are issues about the temperature limit (~100℃) above which bentonite cannot be used.

Initially, it appears that the most promising material for any low-temperature SSM is some form of cement (Woodward-Clyde Consultants, 1983) because they are relatively inexpensive, can be pumped down-hole in their more fluid forms, remain soft long enough to be emplaced, have high compressive strengths when set and excellent radiation shielding properties (although the latter is of little benefit in DBD). Also, there is considerable experience of working with cementitious grouts in the drilling industry. In previous papers on DBD, Gibb *et al.* (2008a, 2008d) suggested that a cement grout was simply 'pumped down the borehole' through the drill pipe following the emplacement of the waste package(s). This assumes the cement would settle into the annulus between the container and casing and, ideally, into the gaps between the casing and rock before setting. However, emplacement of a cement SSM is a more complex engineering challenge, and cementing operations are some of the most difficult and uncertain procedures the drilling industry has to undertake, with frequent failures.

Before a cementitious SSM could be considered for use at the depths, pressures and temperatures of a DBD a number of specific challenges must be addressed. The research programme under way at the University of Sheffield (see Section 4.10) seeks to integrate borehole delivery engineering with a modelling and experimental study of cement formulations and their properties. The objective is to find or develop a suitable formulation and delivery method such that a cement-based SSM can be implemented successfully in the DBD of low heat-generating radioactive wastes. Preliminary studies indicate that the commercially available formulations used by the hydrocarbon and geothermal energy industries (mainly for cementing casing) and their emplacement methods are unlikely to deliver the 100% seal and zero failure rates required for DBD of nuclear wastes. Two principal approaches to the challenge imposed by these requirements are being investigated. In the first, the waste packages are emplaced singly or in batches of less than five followed by the cement, which has to find its way into all the necessary spaces before setting. In the second, delivery of the cement precedes emplacement of the waste package(s), which then has to sink completely into the cement before it sets. Both approaches have significant implications for the number of packages that could be emplaced at a time (i.e. the size of a batch) and for the key properties of the cement SSM, such as rheology, setting and thickening times, hardening and mechanical properties, geochemical reactivity and durability.

8. Borehole sealing

It is important that the borehole itself does not provide an easier route back to the surface for fluids or gasses carrying radionuclides than does the host geology, so it must be completely and permanently sealed above the topmost waste package. Hydrocarbon and geothermal energy wells are sealed in different places using a range of methods and materials, but emplacing these seals is not straightforward and there are engineering challenges in anchoring and/or sealing casing to the wall rock in such holes.

For DBD of radioactive wastes the contact between the seal and wall rock has to be good and would therefore require removal of the casing. Cutting the casing in or above the disposal zone and withdrawing it, as suggested by Gibb *et al.* (2012), is an engineering challenge and a simpler, more cost-effective alternative would be to cut or grind away several metres of the casing at the location(s) of the seal(s) to expose the wall rock. Irrespective of the sealing material used, the contact between it and the rock is a potential surface of weakness that could be exacerbated by longitudinal pressures in the borehole, tectonic stresses or chemical reactions between the seal and saline groundwaters at elevated temperatures and pressures. This could become a path of least resistance to any fluids seeking to flow up or down the borehole.

The presence of an excavation damage zone (EDZ) around the borehole is a significant complication. In hard rocks such as granite this may be restricted to a few tens of centimetres, but it would be almost impossible to get any sealing material, even in pressurised contact, to penetrate far enough into the micro-fractures of the EDZ to make it impermeable to fluid flow. A permeable EDZ is a potential by-pass of the borehole seals and must be blocked off or at least locally eliminated, possibly at intervals above the disposal zone.

8.1 Conventional methods

Sealing of boreholes in the oil and gas industry is commonplace and important, more so in recent years as well integrity has become such an important matter to the public minds and for operational reasons. Zone isolation and annular sealing is particularly important in high-pressure gas wells and gas storage wells.

To support these demands, the oil and gas industry has evolved a wide range of mechanical and cement-related devices and installation methods. New products appear on the market regularly including, in recent years, the ‘swell packer’ (Durongwattana *et al.*, 2012; Kennedy *et al.*, 2005) whereby an elastomer shell around a casing, for example, reacts with water or oil to form a swelling seal to block flow through an annulus. Other equipment such as casing packers can be inflated with cement to seal off an annulus and cement can be pumped under pressure through ports in the casing and ‘squeezed’ into the cavity, much like grouting with the tube-à-manchette system used for dam and tunnel grouting.

In most countries regulation requires that oil or gas wells from which extraction is finished are sealed to ensure that no hydrocarbons or other geopressurised fluids can reach the surface in the future. This is achieved by setting various mechanical and cement or cement-bentonite plugs and sometimes filling the whole well with a cementation compound in stages. Even in high-pressure gas scenarios, the possibility of gas leakage is remote after this sealing process has been completed. In the case of DBD any gas that might act as a carrier for radionuclides would be largely in solution at the disposal depths because of the pressure. If the solution migrated towards the surface up the borehole and the carrier gas exsolved, it would do so at relatively low pressures and could be blocked by the use of these methods, although they would require adaptation of the existing equipment and technology both for annuli between casing and wall rock and for the borehole itself.

There are, however, two aspects of DBD in which uncertainties must exist over the performance of these physical and mechanical methods for sealing the borehole above the waste packages. The first concerns the length of time for which their performance can be guaranteed and it seems unlikely that this could extend to the hundreds of thousands of years required for DBD. The second relates to the EDZ and the difficulties of eliminating it described above. Inflated packers would not affect the EDZ and cements and other grouts are unlikely to render it impermeable on the spatial or temporal scale needed. Consequently, while conventional seals may be adequate in the short term, the development of better and longer lived seals presents a R&D challenge.

8.2 Rock welding

To create a seal as strong as the host rock and eliminate the EDZ, Gibb *et al.* (2008b, 2008c, 2012) proposed that a short length of the borehole, from which the casing has been removed, be backfilled with finely crushed granitic host rock that is then partially melted, along with a significant thickness of the wall rock, by down-hole electrical heating. On cooling slowly the melt recrystallises to a holocrystalline rock virtually identical to (and continuous with) the host rock, thus eliminating the EDZ and sealing the borehole. This process is known as ‘rock welding’.

Rock welding could be repeated at intervals, as determined by the geological conditions and environment, above the topmost waste package with the borehole being backfilled between welds or sealed by more conventional methods as a form of additional insurance. Ideally, the borehole should be sealed within the upper part of the disposal zone to avoid the need to remove more than a single layer of casing and as short a distance as possible above the top waste package to maximise the geological barrier provided by DBD.

A rock welding R&D programme under way at the University of Sheffield consists of six integrated activities

- development of a baseline engineering concept
- heat flow modelling
- melting and recrystallisation of granitic rock
- design of down-hole heaters
- deployment engineering
- full-scale trials.

The baseline engineering concept involves backfilling the borehole for a few metres above the top waste package with crushed host rock then inserting a bridge plug, a simple cement

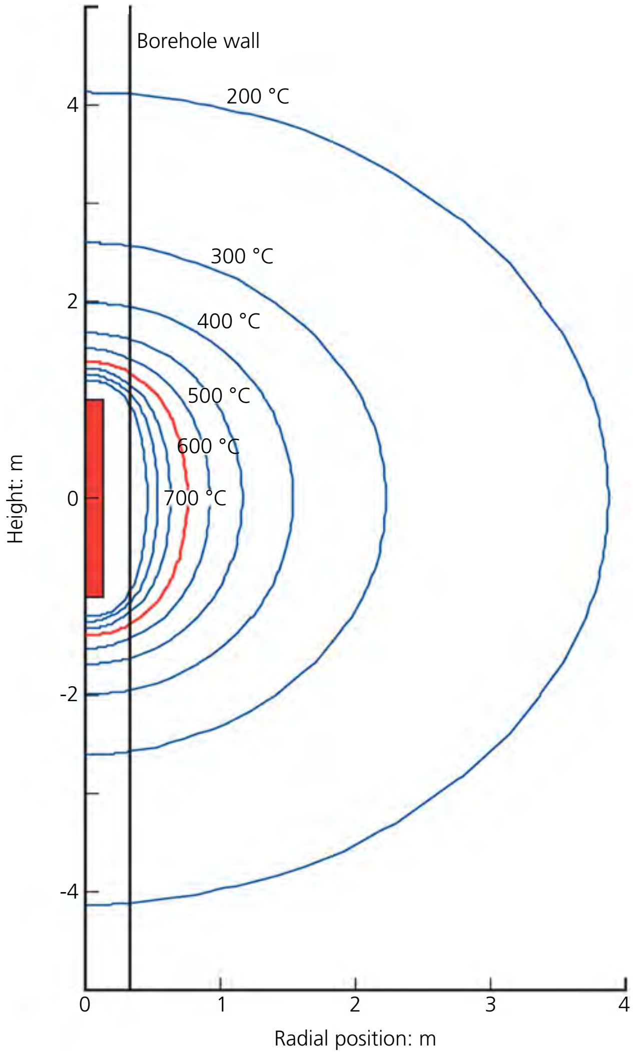

Figure 7. Peak temperatures generated during rock welding in and around a 0·66 m diameter borehole using a 2 m × 0·264 m diameter heater with a power input of 12 kW. Isotherms are at 100°C intervals with the 700°C isotherm (approximate granite solidus) as the thicker line

plug, or both. The disposal zone casing is then cut away for several metres above the plug to expose the wall rock and the hole is flushed with clean water. The hole is filled almost to the top of the exposed wall section with a dense slurry of crushed host rock and the solids are allowed to settle. A sacrificial electric heater, connected to the surface by a retrievable umbilical cord is then placed on top and allowed to settle a short distance into the slurry before more crushed host rock is added to backfill the hole for several metres above the heater. Finally, a pressure seal or packer, through which the umbilical cord passes, is set above the backfill. Power is supplied to the heater to partially melt the enclosing backfill and the host rock for an appropriate distance beyond the borehole wall. The viscous silicate melt flows into all the gaps accompanied by upward migration of the supercritical fluid phase and slight settling of the heater. After a predetermined period of weeks, the power is cut or reduced gradually so the melt recrystallises completely by the time it reaches its solidus temperature. This should take a matter of months.

Heat flow modelling (see Section 6) of various heating scenarios using purpose-designed software (Gibb *et al.*, 2008b, 2012; Travis *et al.*, 2012) predicts the three-dimensional distribution of temperature with time in and around the borehole. The results are combined with knowledge of the melting and crystallisation of granitic rock to ascertain the conditions required for the creation of rock welds of various shapes and sizes.

Attrill and Gibb (2003a, 2003b) showed that granite can be partially melted and recrystallised under attainable conditions and on practical timescales in the context of DBD. This experimental work was carried out at a pressure of 150 MPa (1500 bar), corresponding to ambient pressure 4 km down in continental crust, whereas the pressure at the top of the disposal zone in a water-filled borehole would only be around 30 MPa until the hole is sealed and pressure gradually recovers to ambient. However, refinement of the experimental work for lower pressures will not affect the phase relations significantly and is likely to revise temperatures upwards by only a few tens of degrees. Adequate partial melting of the granitic host rock for rock welding would require temperatures between 700 and 800°C and, under appropriate cooling conditions, the melt would be completely recrystallised on cooling to approximately 550°C. Once a site for DBD has been selected, further experimental work can refine the data for the actual host rock.

The outcomes of the heat flow modelling are used to inform the designs of the down-hole heater packages. A simple example is shown for a 0·66 m (26 in) diameter borehole (see Section 4.8) in Figure 7. The heater is 2 m long with a diameter of 0·264 m and a power density of 110 kW/m^3, corresponding to an input of 12 kW. It is assumed to be made of homogeneous material with a uniform heat generation, neither of which would be the case in practice, when more sophisticated designs would be used, but this is adequate to confirm that rock welding could be achieved with quite modest power inputs on a realistic timescale. Furthermore, temperatures down to approximately 500°C, while too low to melt the host rock, could anneal out any pre-existing microfractures, for example, in the EDZ. The shape and size of the weld can be controlled by varying the length and diameter of the heater, the power input and the distribution of heat output within the heater. The challenges currently being addressed for heater design are to

- ensure that the welds are large enough and have sufficient physical strength to seal the borehole and eliminate the EDZ
- avoid temperatures inside the heater being unacceptably high from the perspective of the materials used to construct it
- generate the temperatures necessary for melting the host rock to the required distance from the heater in suitably short times.

In the latter context it would not be cost effective or practical to have to continue supplying power for periods of many months or even years.

Suitable heaters can be developed to operate under the pressures, temperatures and the chemical environment of DBD, but some challenges, or at least developments, remain regarding down-hole deployment. Like the waste packages, the heater would have to be lowered down-hole and the best method would appear to be coiled tubing (see Section 5.2.4). It is already known that the necessary levels of power can be supplied to the depths involved by means of an umbilical cord. Similar or higher levels of power are supplied by this means to remotely operated submersible vehicles, which operate at greater depths and pressures than in a DBD. However, the engineering required to get the umbilical cord inside the coiled tube and through the pressure seal/packer above the rock weld zone has yet to be worked out in detail.

The eventual construction and testing of the heaters and the demonstration of successful rock welding require large, if not full, scale trials. However, provided the trial can be engineered to contain pressures around 30–40 MPa in the weld zone, it should prove possible to undertake this in a relatively shallow borehole, for example, in a quarry (see Sections 4 and 7.1), allowing easy access to the outcomes.

9. Conclusions

DBD offers an attractive alternative to relatively shallow mined repositories for many forms of HLW, including spent fuel, at substantially less cost per mass unit and with other significant advantages.

Even using current technology, albeit that the borehole diameters are larger than are normally required for other drilling applications, the gap between what can be achieved in deep drilling and the equipment and technology necessary to construct a borehole for DBD has narrowed to the point that a demonstration borehole should be seriously considered as soon as possible. Only then would the remaining issues be resolved and the viability of DBD as an option for the disposal of radioactive wastes be widely accepted.

Some technical challenges remain, mainly related to modification or upgrading of down-hole drilling and casing equipment and the crucial matter of borehole sealing, together with relatively minor details such as designing a waste package running and release tool and the surface shielding arrangements – the latter being well understood by the nuclear industry.

All the main surface equipment required is already available and proved. A concerted effort to address the remaining challenges is overdue. The costs of implementing a (non-active) full-scale, demonstration borehole are small compared with what has already been spent on other options.

The principal obstacle to the implementation of DBD is not really an engineering issue, but is the need for a comprehensive safety case (Chapman, 2013). The works of Brady *et al.* (2009) and Arnold *et al.* (2013) are a good start, and a successful borehole demonstration would confirm the engineering viability, but much remains to be done to gain regulatory approval for the disposal of radioactive wastes.

A successful demonstration should remove doubts about the viability of this potentially superior option, but further progress clearly requires acceptance of the concept and support by government and/or national waste management organisations as appears to be happening in the USA.

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