Deep Borehole Disposal: Options, Issues and Challenges – 16250

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ABSTRACT

Different versions of deep borehole disposal vary in approach and detail and the differences raise issues and create options that need to be considered in the design of any practical implementation. Among the areas for which significant options exist are the size and depth of the disposal zone; container materials and design; the method and strategy for waste package deployment; filling of the annuli around the waste packages and the final sealing of the borehole. The options for these and other areas are discussed with a focus on their advantages and disadvantages and some conclusions reached that could provide guidance for the practical application of the concept. One particularly significant point is that the integrity of the final borehole seal(s) may not be required to survive for as long as is widely believed.

INTRODUCTION

Deep borehole disposal (DBD) is now regarded as a credible alternative to mined and engineered repositories for the geological disposal of high-level radioactive wastes (HLW), including SNF. A recent account of the concept, the underlying science and its potential benefits is given by Beswick et al. [1]. During the last 35 years numerous versions of the DBD concept have been proposed for various types of waste but, with only a few exceptions (e.g. [2, 3]) these have not gone beyond general engineering design. It has usually been assumed that the precise technologies for drilling and casing the boreholes and emplacing the waste packages would simply be modifications or developments of existing practices in the drilling industry. Similarly, the packaging, sealing, handling and transport of the wastes to the well head would be undertaken using the same methods, equipment and facilities developed by the nuclear industry for waste packages intended for interim storage and disposal in mined repositories. The flexibility afforded by these not unreasonable assumptions has meant that the versions can differ significantly from each other in purpose, approach, design and detail. These differences raise important issues and create options that require consideration and evaluation in optimizing the final design of any borehole scheme and could present challenges, including R&D challenges, for the implementation of DBD.

The purpose of this paper is to highlight some of the more important aspects of DBD for which options exist and discuss them with a focus on their advantages and disadvantages. While it may not always be possible to arrive at a conclusion or recommendation without further R&D, this should help to reduce uncertainty and provide guidance for the development of DBD. It should also facilitate progress towards the best engineering design for the DBD of any particular type of waste, especially from the perspective of long-term containment and safety.

DISCUSSION OF ISSUES AND OPTIONS

Option Selection

Notwithstanding the depth and diameter, drilling and casing a borehole for the DBD of radioactive waste and constructing the well-head facilities for the reception, storage and transfer to the borehole of the waste packages are large engineering projects like any other. Problems are likely to be encountered but these can be tolerated and remediated by the usual methods with only the normal operational safety requirements. However, as soon as the first radioactive waste package arrives on site it becomes a nuclear facility and from this point on any unplanned intervention, especially down-hole, could be extremely difficult and potentially hazardous. Consequently, the success of all subsequent operations and procedures must be guaranteed as far as possible. Where options exist for these, the primary criterion for choice must therefore be safety and, in particular, simplicity, minimal risk and maximum reliability: i.e. they must be as failsafe as reasonably achievable.

Borehole Parameters

The logical starting point for any discussion of options is the borehole itself, the design of which begins with the depth and diameter of the disposal zone (DZ). The exact position of the top and bottom of the DZ are site-specific, although in conceptual versions an ideal DZ is usually specified. The DZ borehole diameter “should be governed by the sizes of the waste packages required to optimize the potential application” [1] which, in turn, depend on the nature and type of the waste. Examples of DZ dimensions that have been suggested for various applications are given in TABLE I

TABLE I. Examples of Proposed DZ Borehole Dimensions

Diameter of Borehole DZ *(mm)*	*(inches)*	**Top of DZ** *(km)*	**Base of DZ** *(km)*	**Proposed Waste**	**Reference**
216	8.5	3	5	Hanford cesium capsules	Travis & Gibb [4]
270	10.6	4	6	Plutonium	Gibb et al. [5]
432	17	3	5	Consolidated SNF rods	Arnold et al. [6]
444.5	17.5	1.5	5.2	Consolidated SNF rods	Brady et al. [7]
508	20	2	4	Complete SNF assemblies	Hoag [8]
560	22	3	4	Consolidated SNF rods	Gibb et al. [9]
610	24	2.5	5	Reprocessing waste glass	Beswick et al. [1]
800	31.5	2	4	Complete SNF assemblies	Juhlin & Sandstedt [10]
838.2	33	2	4	Complete SNF assemblies	Harrison [2]

All of these diameter and depth combinations were considered achievable with existing drilling technology by their proposers and, with the possible exception of the two largest, should now be regarded as within the capability envelope of the drilling industry [1, 11] and are therefore realistic options. The last two are probably still the major challenge to the drilling industry that Harrison [2] believed.

Casing

DBD requires that the borehole be drilled and fully cased in, usually [1, 6], four stages of downward decreasing diameter. The lowermost (DZ) casing should extend to the surface [1, 9] or have tie-backs of the same diameter [6] to the top of the hole. This is necessary to provide a smooth, continuous, constant diameter tube from the top to the bottom of the hole to minimize any risk of waste packages snagging during emplacement. Most recent DBD versions agree that the innermost casing should be perforated throughout the DZ. This reduces weight, allows equalization of borehole pressures and enables movement of fluids between the inner and outer annuli (see below). The size of the perforations should be less than the clearance between the casing and the waste packages to prevent any fragments of wall rock that might impede package emplacement getting through.

From the perspective of stability it is advisable that casings are cemented as well as they can be but cementing or otherwise filling the annulus around the DZ casing is an important issue and is dealt with separately below. Most schemes advocate cementing of any intermediate casings even where sections of the casing are to be cut or ground away later to allow access to the wall rock for borehole sealing [1, 12]. However, some schemes, e.g. [3, 6], require that most of the intermediate casing above the DZ be withdrawn once package emplacement is complete to give access to the wall rock for sealing purposes. Such an operation could be very difficult in practice and almost impossible if the casing was cemented in so only the lowermost 10% or so is cemented for stability. Consideration of cementing options should be integrated with the proposed locations of the borehole seals which require site-specific characterization of the geology and hydrogeology.

Waste Package Deployment

There are two main aspects of waste package deployment for which important options exist: the method of down-hole emplacement to the DZ and the choice between deploying the packages individually or in multiple strings.

Emplacement Method

There are essentially four methods available for package emplacement: free fall, drill pipe, wireline and coiled tubing.

Free fall (or ‘drop in’) involves simply releasing the package at the top of the borehole and relying on the hydraulic damping effect of the borehole fluid to control descent speeds. These speeds are mainly a function of the package mass, the clearance between the package and casing and the properties of the fluid. It is crucial that terminal velocities are kept down to less than about 3m/sec to eliminate any risk of damage to the containers on impact with the bottom of the hole or previously emplaced packages. If perforated casing is used in the DZ descent speeds are likely to increase through this part of the borehole due to displacement of fluid through the perforations and due allowance must be made. If terminal velocities cannot be kept low enough, potential damage can be eliminated by fitting the packages with impact limiters [3] or the use of denser, more viscous fluid. Free fall allows the fastest deployment times with one-way trip times to 5 km of 1.5 to 3 hours but does not allow any control of the descent, positional monitoring or other feedback. Also there is no provision for releasing stuck packages or recovery.

Drill pipe is the emplacement method advocated for most versions of DBD. It is a well-tried and reliable method for all forms of down-hole intervention in the drilling industry. Its main advantages are that it can handle heavy loads, affords precise depth control and allows for two way rotation of the waste packages if required. It enables accurate release of the packages and facilitates recovery while the added weight of the drill pipe can aid descent through dense or viscous deployment fluids. Unfortunately the need to screw together the lengths of pipe one, two or three at a time makes it very slow with round trip times in excess of 24 hours [1, 3]. It also requires skilled operatives to achieve reasonable speeds and necessitates that the drill rig, or a replacement workover rig, is kept on site throughout the deployment stage. The use of drill pipe also carries the risk of serious accident if a length of pipe is inadvertently dropped onto the waste packages in the DZ. The weight and large clearance between the pipe and casing could result in rapid descent and a terminal momentum that could penetrate the containers and lead to radionuclide release. Safety measures would need to be put in place to prevent this.

Wireline is the traditional way of speeding up down-hole activities in the drilling industry. Its main advantages for waste package emplacement would be cost and potentially very short round trip times. Disadvantages include load limits (although these are increasing with modern materials), stretching problems and the need for additional measures for positional monitoring. Also, fast running carries the risk of entanglements that need to be avoided and necessitate caution, especially during the initial stages of the down trip, with the result that round trips to 5 km could take over 6 hours in practice.

Coiled tubing is a relatively recent means of undertaking down-hole operations that has been successfully developed and used in the oil and gas industry where it has been run to over 10 km. Once the casing has been set a much smaller coiled tubing unit (Fig. 1) could take over from the drill rig for deployment, borehole sealing etc. (see below). The steel tubing comes on a large drum in various diameters and wall thicknesses and can

Fig. 1. Typical Coiled Tubing Unit

take loads of over 40 tons. It is reliable and fast with round trip times to 5 km of less than 6 hours, and it offers the option of electrical conductors inside the tube, raising all sorts of possibilities for remote operations, depth control, descent monitoring and package recovery. Its only disadvantage is that the flexing of the tube over the goose-neck at the well-head and winding round the drum creates metal fatigue that limits operational life. However, for waste package emplacement, depending on the exact tubing used and the loads involved, between 100 and 200 round trips to 5 km could be made before replacement becomes necessary. With replacement costs between $130,000 and $220,000 (depending on size) the price per trip would make coiled tubing quite cost effective.

Deployment by free fall should not be considered for DBD because of the lack of control and recovery problems. Unless necessitated by the loads involved, deployment by drill pipe should be avoided because of its slow round trip times, the need to keep the rig on site throughout deployment and the risk of accidental drop of a length of drill string. There is probably little to choose between wireline and coiled tubing in terms of speed and cost but the greater reliability, options for recovery, enhanced down-hole operations and the fact that it could be used for subsequent procedures such as sealing weigh strongly in favour of coiled tubing.

Multiple Emplacement

Most DBD versions deploy the waste packages one at a time with any subsequent operations in the DZ (see below) carried out after the emplacement of each package or small batch of packages. Woodward Clyde [13] raised the possibility that the packages could be assembled into strings at the top of the borehole and lowered in a single operation. This idea was carried through work at Massachusetts Institute of Technology on package design and deployment [8] and evolved into 400 m long strings of 40 SNF packages weighing almost 70 tons [6]. Such loads could only be emplaced by drill pipe and the combined weight of the packages plus up to 5 km of drill pipe, collars etc. would need a powerful drill rig. Individual packages could be assembled into strings either by using external, upset couplings or by cleverly designed internal threads machined into the ends of the containers [3]. Upset couplings have the disadvantage of reducing clearance between the package and casing and could necessitate a reduction in the diameter and capacity of the containers. In both cases the result is a rigidly coupled string of waste packages with little or no flexibility along a length of up to 400 m. This places severe constraints on the dogleg severity and tortuosity of the borehole if the string is not to get stuck.

In addition to the sophisticated coupling arrangements, the assembly of strings of waste packages at the top of the borehole requires the installation of special equipment below the shielded transfer facility that up-ends the waste package and inserts it into the hole (horizontal transport to the site is assumed) [3, 8, 13]. This equipment includes remotely operated rams, slips, collars and tongs for holding the packages and screwing them together (and unscrewing, if necessary) as well as monitoring and safety devices. These increase the size and cost of the well-head facilities but the main disadvantage is that each package spends much more time at the top of the borehole than it would if emplaced singly and lowered directly to the DZ. These complex operations inevitably increase the risks of delays, accidents and workforce exposure. Also, for high heat generating waste packages a protracted time immersed in aqueous fluid at near atmospheric pressure at the top of the borehole may not be advisable and could necessitate additional safety measures.

The rationale behind the original suggestion for assembly into strings was to reduce the time for emplacement by saving on a number of lengthy individual round trips at a time when there was no alternative to emplacement by drill pipe. The availability of fast, reliable individual package emplacement by modern wireline or coiled tubing could negate this rationale, especially as a single package could be emplaced in the DZ in less time than it could be added to a string at the well head [3]. Given that the limiting factor for filling the DZ is likely to be the rate at which waste packages can be delivered to the well head – one per day is a generally quoted figure – the justification for the complexity, risks and cost of multiple package emplacement needs to be re-examined.

Deployment Fluids

At the depths and pressures involved it is almost inevitable that the borehole will have to be drilled using a dense, probably clay based, drilling mud. Some DBD schemes, e.g., [6], would leave this in the borehole and emplace the waste packages through it. Others would use a special deployment mud, again clay based, with properties that facilitate package emplacement while yet others, e.g., [1, 9], would flush the hole out with fresh water and emplace the packages through this.

Keeping dense mud in the borehole mitigates against wall rock relaxation, break outs and rock fall ins (and, in extreme cases, borehole collapse) but once a robust steel casing is set these are unlikely to be serious problems. Where some of the casing is to be cemented as part of the long-term sealing program it is essential that the mud and wall cake is removed from the borehole wall to ensure the best possible cement to rock bond and the subsequent cementing is best done in clean water. If the DZ annuli between the waste package and casing and between the casing and borehole wall are to be filled with some form of sealing and support matrix (see below) they cannot be full of mud. While it is theoretically possible to flush any mud out of them after emplacement of the waste packages it would be preferable to do so before emplacement and ideally before the DZ casing is set.

Unless there are likely to be issues requiring the maintenance of a dense fluid within the well it would be preferable all round to flush the hole clean with water as soon as possible and deploy the waste packages through it. In the event of possible concerns about down-hole pressures it would be possible to use dense brines in place of fresh water to avoid the complications of using mud.

Package Centering

It is important that when they are emplaced the waste packages are centered in the DZ casing. Initially this is to ensure vertical load stresses are coaxial to minimize any possibility of damage to the containers; a risk that would be increased by misalignment. However, it is also necessary to ensure that any sealing and support matrices subsequently inserted into the annulus around the packages (see below) are of uniform thickness and distribution.

Several devices have been suggested to make sure the packages remain coaxial during emplacement including centering rollers, fins and even deployment cages. The simplest and most effective way of achieving this is to fit thin sacrificial fins at 120º intervals around the container or shear pins similarly placed at the top and bottom ends of the container. Any such fins should be made of a relatively soft material, such as aluminum, and designed to detach easily in the event of a package becoming stuck. Likewise any pins, which could be screwed into threaded holes in the container for easy adjustment, should be designed to shear off in the event of problems. Such devices also facilitate an even flow of the borehole fluid past the package and could even be designed to 'spring out' to stop or slow the descent if a package accidentally becomes detached.

Near Field Safety Case

The safety case for DBD frequently stresses the importance of the geological or far-field barriers but it is still very much a multi-barrier geological disposal concept in which the main near-field barriers are the wasteform, infill, container and the annulus between the package and borehole wall. When it comes to the role of these in the long-term safety case for DBD there are two diametrically opposed schools of thought. The first takes the view that, once the DZ is filled and the borehole is sealed above the topmost waste package, any escape of radionuclides into the DZ near field is irrelevant as isolation is ensured by the geological barriers for well over a million years. I.e. the near field barriers do not really matter beyond the point where the borehole seals are in place. The second argues that, irrespective of the isolation afforded by the depth and geological barriers, the near field barriers should be as robust as reasonably achievable, so delaying the need for the far field barriers as long as possible. Pending resolution of this debate, the conservative approach would be to consider the options available for maximizing the near field barriers, the potential advantages and the underlying rationale.

Wasteform

One of the potential benefits often put forward for DBD is that it can take almost any form of solid waste and can cope with almost any amount of decay heat. Many of the candidate wastes for DBD such as SNF (complete assemblies or consolidated fuel rods) or vitrified reprocessing wastes are already in a highly suitable form for disposal. Others, like the Hanford cesium (Cs) and strontium (Sr) capsules, may already be packaged and require only robust overpacks. It could be difficult to justify the risks, effort and costs of further processing and/or repackaging on the grounds of marginal improvements to the safety case. An exception to this could be where a significant reduction in volume could be achieved, such as fuel rod consolidation for LWR assemblies. On the other hand there are wasteforms that are not suitable for DBD but could easily be made so, e.g. fission product calcines.

Infill

It is important that there is no void space within the container to minimize the risk of deformation and possible damage under the prevailing hydrostatic pressures and axial load stresses. For candidate wasteforms that are poured into the container in liquid form, e.g. vitrified HLW, this is essentially the case (there may be a little ullage at the top of the container). For others, like complete LWR assemblies or consolidated SNF rods, there can be considerable space which has to be filled. Various materials have been suggested for this such as sand or cement [14], silicon carbide [15], glass, copper [16] or molten lead [9]. All of these materials have potential advantages and disadvantages and these need careful evaluation, along with other materials, especially if the infill is to function as part of the near field safety case.

Container

Many options exist for the container material. At the more cost effective end of the spectrum are containers manufactured from standard size, carbon-steel drill pipe [3, 6-8, 14] while at the other end, driven by long-term safety considerations, are purpose made containers of titanium [10], copper or bronze [17] and nickel alloys. Most DBD versions opt for steel, usually a stainless steel [1, 2, 9]. The optimum choice depends largely on the mechanical strength required and the extent to which the container is required to resist corrosion with cost and manufacturing issues secondary concerns. The mechanical properties needed for the container are essentially a matter of engineering calculation and design to minimize weight and volume and are probably best met by a strong material like steel or titanium. Where the container has to function as a primary or major safety barrier, as in most mined repositories, corrosion resistance is paramount but for DBD this is less important and adequate protection against corrosion could be created in other ways (see below). Also, possible compromise solutions exist such as lining or plating (or both) a steel container with copper or another corrosion resistant material.

Annulus Filling

Possibly the most crucial components of the near field safety case for DBD are the two annuli between the waste package and the casing and between the casing and the borehole wall. If these are left filled only with water, clay based mud, sand or even incompletely filled by well (casing) cementing, the saline groundwaters will have ready access to the steel casing and the containers and corrosion could become an issue [18]. Further, the annuli could provide an upward migration pathway for any gaseous products of the corrosion reaction(s) such as hydrogen.

It is therefore important that throughout the DZ both annuli are completely filled with some form of sealing and support matrix (SSM) that prevents, or significantly delays, access of the groundwaters to the containers. It is essential that any such SSM is impermeable to water and can be emplaced around the waste packages without leaving any gaps. Achieving the latter at a depth of several km is far from straightforward and requires special materials and methods. The secondary function of the SSM, to provide mechanical support for the containers against deformation by the axial load stresses, is more important during the package emplacement stage before the borehole is sealed.

To date two methods have been proposed for this. The first [19] involves the use of a customized high density support matrix (HDSM) that is deployed around each waste package in the form of a fine lead (Pb) alloy shot. Shortly after emplacement the decay heat from the waste melts the shot to a dense liquid that flows into all the voids in the annuli, via the perforations in the casing, displacing upwards any aqueous fluid. Over time, as the heat from the waste declines, this molten metal re-solidifies completely sealing the waste packages into the borehole. Lead and its alloys do not corrode easily in salt waters as they tend to form a passive protecting layer but it is essential that they completely encase the other metals to avoid the possibility of any galvanic effect in the saline fluids. An additional benefit could be the disposal of unwanted, contaminated lead from the nuclear industry. The disadvantage of this method is that it requires peak temperatures within the annuli in excess of 185^{o}C to melt the alloy, the attainment of which depends on the ambient down-hole temperature and the heat output of the waste. For wastes that do not generate high enough temperatures in the annuli an alternative method utilizes a specially formulated cement grout. Such a grout is currently under development at the University of Sheffield and its properties and use are described by Collier et al. [20]. The durability and useful temperature range of the cement grout have yet to be fully determined but the latter will almost certainly overlap with the HDSM, making the two methods complementary.

If the near field barriers are to be given any credit in the overall safety case and performance assessment of DBD, the issues of waste package support, especially during the filling of the DZ, and protection of the containers against corrosion by the saline groundwaters are crucial. The suitability of the proposed HDSM, cement grout and other potential materials and methods need careful evaluation and optimising for specific DBD programs and site conditions.

Borehole Sealing

If the massive isolation provided by the depth and geological barriers is not to be compromised it is imperative that the borehole itself does not provide an easier route back to the human environment for any radionuclide bearing fluids than does the surrounding geology. Consequently, it has been widely accepted that the DZ must be sealed off from the rest of the borehole for as long as is required for the wastes to become radiologically harmless. This is usually taken to be 10^5 to 10^6 years for SNF but could be significantly less for other candidate wastes.

Conventional Sealing

Most DBD versions have looked to the oil, gas and geothermal energy industries for ways of sealing the borehole. Hydrocarbon and geothermal wells are usually sealed with materials like cement, concrete, clays, bitumen or asphalt. These are simply pumped down the hole, with or without prior removal of a section of the casing (if present), and allowed to harden or set. Alternatively, mechanical devices (packers) into which materials like cement can be pumped or swell packers (a steel plug enclosed in an elastomer that swells on contact with liquid) can be used. All of these seals can work well, even under high gas pressures, but they are difficult to emplace, unreliable with frequent failures and have only been proven to retain their integrity for a few decades.

The Sandia National Laboratories (Sandia) "reference design" (Fig. 2) probably represents the ultimate development of sealing a DBD by a combination of conventional means. However, no matter how durable the material or how well set the seal is, the interface with the wall rock will always remain a zone of potential reaction and weakness that could become a path of least resistance for any fluids seeking to flow up or down the borehole.

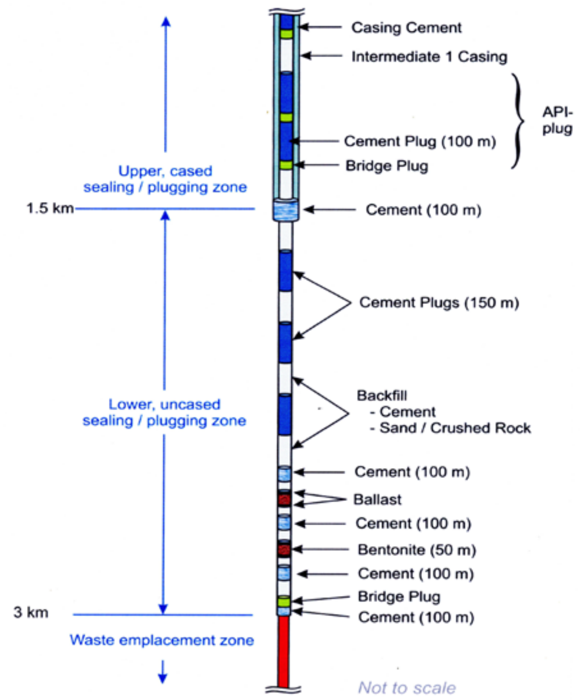

Fig. 2. Sealing by a Combination of Conventional Methods [6].

Innovative Sealing Concepts

One attempt to create an improved seal for the aggressive thermal and chemical environment of DBD is the ceramic plug of Lowrey et al. [21] (Fig. 3) based on the thermite process. A section of the casing is ground away and a metal oxide charge is emplaced and ignited from the bottom. It progressively self-sinters upwards and on cooling leaves a robust and durable oxide plug.

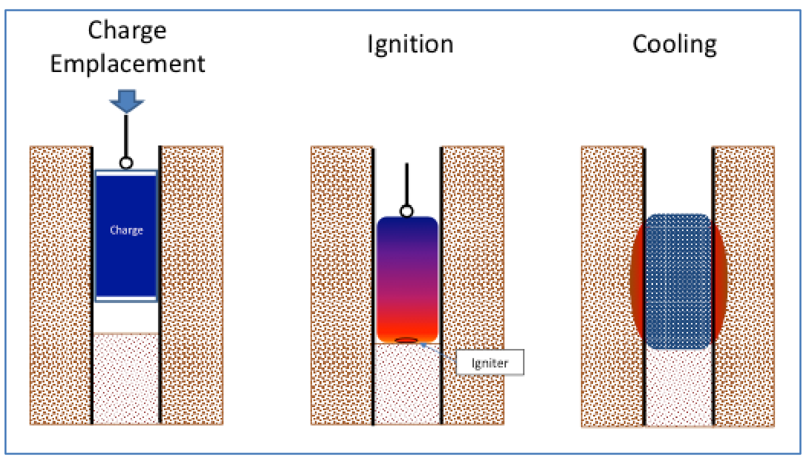

Fig. 3. Ceramic Plug Seal for DBD [21]

Recognizing the difficulties in emplacing and maintaining the effectiveness of swelling clay based seals, Pusch et al. [17] have developed improved systems for their use and addressed the problem of retaining their integrity over long periods. These are based on large, perforated, copper or bronze supercontainers (Fig. 4) similar to those that could be used for the disposal of waste packages. The seal supercontainers would be filled with pre-compacted blocks of a smectite clay such as montmorillonite (the main constituent of bentonite) and forced down through a clay-based drilling or deployment mud in the perforated casing of the borehole. As the blocks hydrate and swell out through the perforations they generate a sealing pressure in the clay mud against the borehole wall that could be maintained for long periods.

The Disturbed Rock Zone

Unfortunately, for all the above borehole sealing methods a problem arises from the presence of an excavation damage (or disturbed rock) zone (DRZ) around the borehole itself (Fig. 5). Created during the drilling, this can extend into the rock for a distance that is dependent to some extent on the method used but can be tens of centimeters. The interconnected network of fractures and microfractures increases the bulk hydraulic conductivity of the DRZ, possibly by over two orders of magnitude, compared with the unaffected host rock.

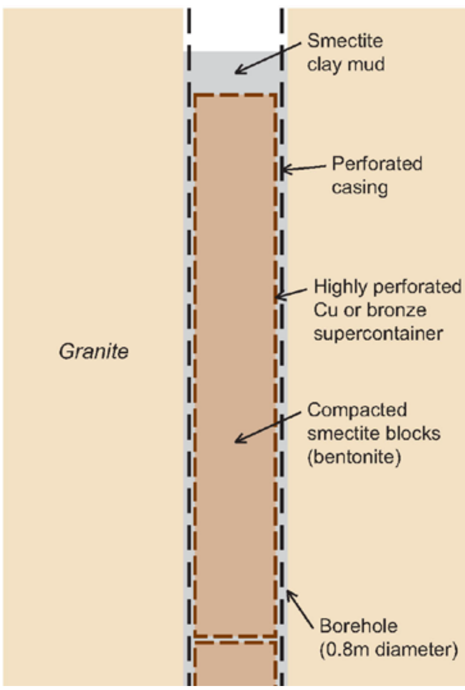

Fig. 4. Supercontainer Based Clay Seals [17]

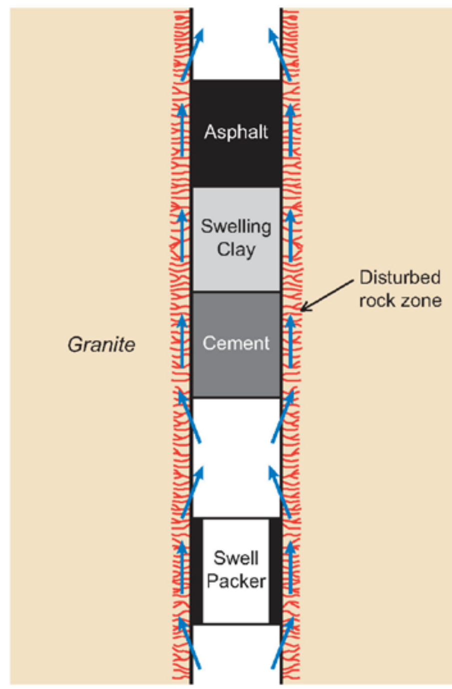

Fig. 5. Schematic of Disturbed Rock Zone Around the Borehole

No seal material, even one emplaced under pressure or generating swelling pressure on the borehole wall, e.g. [17], could penetrate completely into these fracture networks and reduce the bulk hydraulic conductivity to the levels of the original rock. The DRZ would therefore always remain a potential by-pass of all the above seals for any radionuclide carrying fluids seeking to flow up the borehole. A possible exception to this might be the ceramic plug [21] if the heat generated could penetrate into the wall rock and anneal out the DRZ fractures. However, in the absence of controlled slow cooling (see below), heating of the rock could result in contraction fractures and exacerbate the situation.

Rock Welding

A method for sealing the borehole that could also eliminate the DRZ is currently being developed at the University of Sheffield. Referred to as “rock welding” this involves partially melting crushed granitic backfill in the hole and the host rock for an appropriate distance beyond the borehole wall by down-hole electrical heating. Recrystallization of the partial melt under carefully controlled conditions results in a zone of holocrystalline granite almost identical to, and continuous with, the original host rock – the “weld”. The stages in the process are shown in Fig. 6 and a more detailed description of the concept and the underpinning science are given in [12].

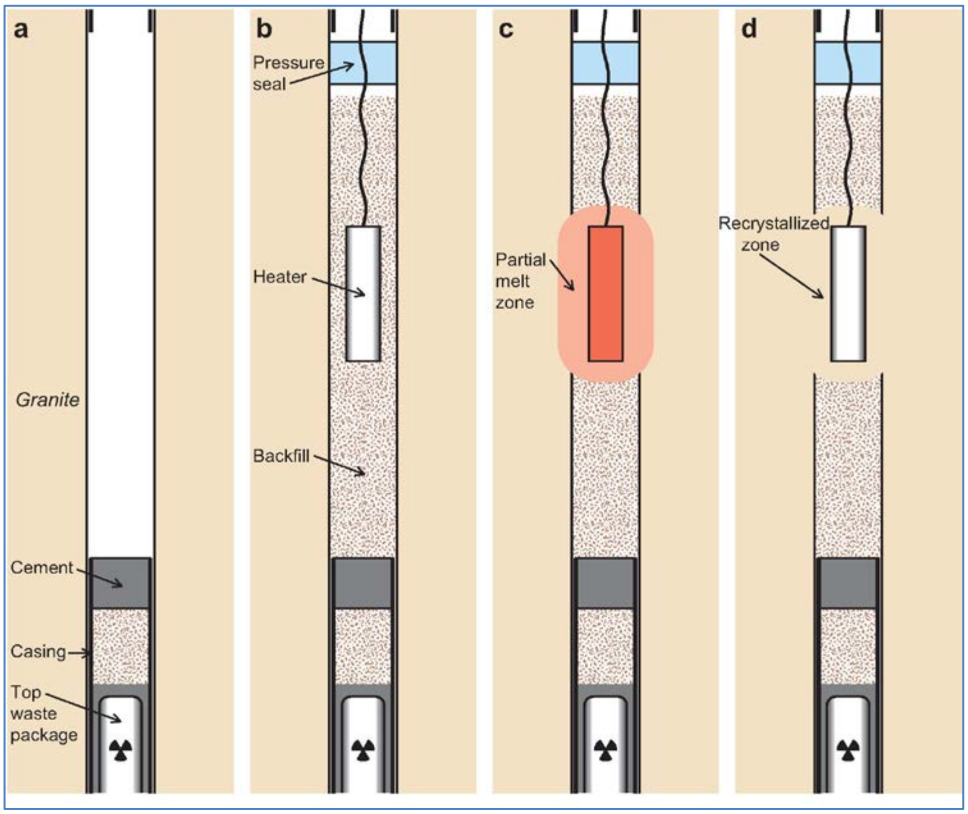

Fig. 6. Schematic Showing the Stages in the Rock Welding Process [12]

The rock welding is done above, and as close as possible to, the topmost waste package, ideally within the DZ. It can then be repeated at intervals up the borehole as required by the geology, e.g. the distribution of fracture zones. Between rock welds the borehole can be sealed by other methods and materials or backfilled. The heating and cooling cycle could last between a few months and two years with the latter depending on the size of weld required and the exact down-hole conditions.

Seal Performance

The above consideration of sealing methods is based on the presumption that the DZ must be isolated from the overlying parts of the borehole and denied access to the near-surface environment by some human engineered system. However, this may not be so. While the borehole is open and filled with aqueous fluid less dense and saline than the brines in the host rock, hydrostatic pressures will result in a slow flow towards the hole. Once activities in the borehole (package emplacement, annulus filling, casing cutting/withdrawal, backfilling, sealing, etc) are completed and the hole is sealed and filled above the DZ, the lateral pressure gradients will level out and the vertical salinity gradients in the surrounding host rock will gradually become re-established in the borehole. This will then act as an obstacle to fluid flow up the borehole just as it does in the host rock.

It may therefore be the case that the DZ need only be sealed off from the rest of the borehole long enough for the decay thermal high from the waste, which could result in some transient convection, to have passed and the salinity gradients in the rock to become re-established in the borehole. For wastes like SNF the period of significantly elevated decay temperatures is likely to be less than 200 years.

The time required for the salinity and density gradients in the groundwaters to re-equilibrate within the borehole is a function of the site-specific hydrogeological conditions together with the properties of the materials in the sealed borehole. A research project underway at the University of Sheffield aims to quantify this process and create a numerical model into which geological and hydrogeological data from the borehole and beyond can be fed. This should enable prediction of the recovery period for the salinity gradients in the borehole for a range of variables and hence define how long the borehole seals would need to maintain their integrity. This could turn out to be as little as a few hundred years.

If this is the case, it could be a major game change for borehole sealing which is possibly the most important remaining R&D issue for DBD. However, until this can be demonstrated and substantiated by down-hole measurements of salinity gradient recovery, e.g. in characterization boreholes, the presumption must remain that the DZ should be isolated for as long as possible.

CONCLUSIONS

From the foregoing discussion of options for some key aspects of DBD the following conclusions may be drawn.

The diameter of the borehole in the DZ should be within the envelope of currently achievable depth-diameter combinations but otherwise would be determined by the need to optimize the application. The borehole should be fully cased with the final casing extending to the surface (or with tie-backs) and being perforated in the DZ. The cementing of any intermediate casings should be integrated with the geology and the borehole sealing strategy.

The waste packages should be deployed singly by wireline or coiled tubing with the latter offering many advantages. Deployment should be through clean water or brine with the packages centered in the DZ casing. The choice of container material and design should be governed by the application but must satisfy the requirements of physical strength and corrosion resistance. The latter must be ascertained in conjunction with the DZ annulus filling strategy. In the latter context it is strongly recommended that the annulus be filled with the most appropriate SSM, especially where steel containers are involved, to prevent or delay corrosion and eliminate a potential gas migration pathway. Final borehole sealing should involve a combination of methods and take full account of the extent of the DRZ.

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