SEALING DEEP BOREHOLE DISPOSALS OF RADIOACTIVE WASTE BY "ROCK WELDING"

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For the safe disposal of radioactive wastes in deep boreholes the hole must be properly sealed above the disposal zone so that it does not provide an easier route back to the biosphere than the surrounding geology for any radionuclide bearing fluids. Conventional hydrocarbon and geothermal well seals are unlikely to last the 10^5 or more years required for the isolation of high-level radioactive wastes. Also, they cannot eliminate the zone of damaged rock around the borehole that could act as a by-pass for any radionuclide bearing fluids. We propose instead an innovative concept for sealing deep borehole disposals - "rock welding". This process involves partially melting crushed granite backfill and the granitic wall rock with energy from a down-hole electric heater. Controlled cooling allows the melt to recrystallize to a holocrystalline rock identical to, and continuous with, the host rock in almost all its properties except grain size. Experimental work confirms that such melting and recrystallization are possible under achievable conditions in a deep borehole. Further, thermal modeling demonstrates that rock welds large enough to seal the hole and locally eliminate the zone of damaged rock can be created on a time scale consistent with a disposal program.

I. INTRODUCTION

Disposal of spent nuclear fuel (SF) and other high-level radioactive wastes (HLW) in fully cased, large diameter, boreholes sunk several kilometers into the granitic basement of the continental crust offers many advantages over mined repositories[1-3]. This deep borehole disposal (DBD), while still a multi-barrier concept, places more emphasis on the natural geological barrier and less on the engineered barrier system. In particular, it capitalizes on the isolation provided by the much lower bulk rock hydraulic conductivities and the density stratified saline groundwaters generally found at greater depths. However, if these benefits are to be fully realized it is crucial that the borehole itself does not provide an easier route back to the biosphere for any potentially radionuclide bearing fluids than does the enclosing geology. It is thus important that the borehole is completely and permanently sealed above the disposal zone (DZ) containing the waste packages.

Some DBD schemes propose that the borehole above the DZ is sealed more or less continuously all the way up to the surface while others suggest it may be enough to seal the hole at intervals above the DZ with backfilling between the seals. Either way, the sealing should begin as short a distance above the topmost waste package as possible in order to maximize the geological barrier. Sealing within the upper part of the DZ also has some practical advantages[3].

By contrast, there is a school of thought (notably in Sweden) that considers any sealing or backfilling of the borehole above the DZ need only be sufficient to prevent or impede convective flow of fluids in the borehole during the initial period of significantly elevated temperatures in the DZ. For disposals such as SF this period is likely to last for a few hundred years. This view is based on the premise that, once filling and other activities in the hole cease, the groundwater salinity and density gradients in the host rock will gradually become re-established in the borehole and these will be sufficient to prevent upward migration of any fluids containing radionuclides that might eventually escape from their primary containments within the DZ.

Given the uncertainties about the extent and timing of re-establishment of salinity gradients in the latter case and the potential for thermally induced convection in the early stages of any disposal, we believe that –

a) waste packages should be individually sealed into the DZ as well, and for as long, as possible[3-5] and
b) that the borehole should be sealed above the DZ so it does not provide a path of less resistance to the migration of fluids than does the surrounding geology for at least 10^5 years.

These measures are necessary to maximize the long-term safety case for DBD. Here we review briefly the methods of sealing boreholes and present an innovative approach to the creation of seals with the same properties as the host rock and which cannot be by-passed by migrating fluids.

II. CONVENTIONAL BOREHOLE SEALS

II.A. Hydrocarbon and Geothermal Energy Wells

In many oil, gas and geothermal energy wells sealing of the wall rock for at least part of the depth is necessary to prevent loss of drilling fluid, oil, gas or steam through high permeability horizons or fracture zones in the host rock. Generally this is achieved by casing the hole over the required interval(s) and filling the casing – wall rock annulus with bentonite (clay), grout, cement or other material. When the well has finished production it is often necessary (and, in many cases, a legal requirement) to close off the well bore completely to prevent the escape of pollutants that could contaminate the near-surface environment. This may or may not require the removal of any casing and can be achieved by emplacing or pumping clay, cement, concrete, bitumen or other seal material down the hole and allowing it to set. Alternatively, there is a range of mechanical devices (packers), often involving elastomer seals that swell on contact with oil or water, that can be used for the same purpose.

When set properly such seals can work well, even under high gas pressures, but emplacing them presents significant engineering challenges[3] and the interface between the rock and the seal will always remain a potential surface of weakness. Longitudinal pressures in the borehole, tectonic stresses or chemical reactions between the seal material and saline groundwaters at elevated temperatures and pressures could exploit this weakness to create a path of least resistance to any fluids seeking to flow up or down the borehole. Further, there exist considerable uncertainties over the longevity of any such seals and it must be doubtful whether their integrity could be guaranteed for the tens, or hundreds, of thousands of years required for SF and HLW isolation.

II.B. Exploration Boreholes for Mined Repositories

Site characterization and other activities related to the construction of mined and engineered repositories require the drilling of exploration boreholes. These tend to be of much smaller diameter than the holes required for DBD but eventually they have to be sealed off in order to not affect groundwater flow through the repository and to meet the requirements of the safety case. Different methods have been proposed for different repository concepts and host rocks but one of the more technologically advanced is SKB's "reference design" for the proposed Swedish SF repository at Forsmark[6].

In this case the uncased borehole is first plugged with concrete then a close-fitting, perforated, copper tube filled with highly compacted bentonite is inserted above the plug and more compacted clay or concrete is placed on top. As water penetrates the smectite-rich bentonite (type MX-80) it hydrates and swells, expanding out through the perforations to form a pressurized seal between the copper tube and the rock. A successful full-scale trial of this concept was carried out at a depth of ~ 500 m in a borehole at the Finnish repository site at Olkiluoto[6]. Other schemes, usually involving compacted smectite-rich clays, have also been proposed including mechanical insertion of clay plugs and using compressed air to "blow in" bentonite pellets. The main problems with all such schemes relate to emplacing the dry compacted clay in a water-filled borehole and ensuring a complete seal (which cannot be inspected after emplacement). Further complications could arise as variations in the actual diameter and non-circularity of the borehole increase, as is likely to be the case for larger boreholes such as those required for DBD.

II.C. Deep Borehole Disposal

Most DBD concepts divide the borehole into the disposal zone (DZ) above which is a "seal zone". The latter is often divided into lower and upper sections of varying lengths. The methods and materials proposed for closing off the seal zone are usually combinations of those used in the hydrocarbon and geothermal energy industries. For example, in the Sandia "reference design"[7] the lower half of the 3 km long seal zone, from which the casing has been withdrawn, contains a series of cement and bentonite plugs separated by volumes backfilled with combinations of cement, sand and crushed host rock. A 1.5 km long upper section, which retains its cemented-in casing, is blocked off at intervals by cement plugs and mechanical bridge plugs, again separated by backfilled volumes.

In the Swedish very deep holes (VDH) concept[8] the 2 km long seal zone consists of a 1.5 km lower section in which the perforated titanium casing is filled with pre-shaped blocks of highly compacted smectite-rich clay and an upper 0.5 km section which is sealed with asphalt or concrete. Recognizing the difficulties of emplacing pre-shaped compacted clay blocks, Pusch *et al.*[9] subsequently proposed a modification of the Swedish scheme in which the casing is made of Navy Bronze and the seal zone is filled with "supercontainers" made from the same material and containing tightly fitting blocks of highly compacted smectite-rich clay. 50% of the surface area of these "supercontainers" is perforations through which the clay expands on hydration and subsequently through the perforations in the casing to fill the voids between the "supercontainer" and the rock. It was also proposed that any fracture zones intersected by the borehole be first stabilized by removing the casing, plugging with concrete and re-boring since clay-based seals can be lost through erosion caused by ground-water flow through fractures[9].

III. THE ENGINEERING DAMAGE ZONE

All tunneling, shaft sinking or borehole drilling operations create a zone of damage in which the wall rock is fractured to a greater or lesser degree. This is known as the engineering (or excavation) damage zone (EDZ), sometimes referred to as the disturbed rock zone[7] or DRZ. For drill holes the size and density of fractures and the distance the EDZ extends out into the wall rock are functions of the lithology, the local stress field and the drilling method employed. It is generally recognized that fracturing and the size of the EDZ are greatest for percussion drilling, less for full-face boring and least for coring[9]. Nevertheless, for a "hard" rock such as granite the EDZ can extend for anything between a few centimeters and a few tens of centimeters beyond the borehole wall. The interconnected fractures and microfractures in the EDZ can significantly increase its permeability, possibly by several orders of magnitude, compared to the virgin rock.

No conventional seal material or device emplaced in the borehole, even under (or generating) substantial pressure, could penetrate far enough into the system of microfractures to render the EDZ impermeable or even restore its pre-drilling permeability. Consequently, it would remain a potential by-pass of conventional seals for any radionuclide bearing fluids. A performance assessment of any DBD using such seals would inevitably identify the EDZ as the dominant release pathway.

IV. ROCK WELDING

Significant uncertainties exist over the sealing of DBD using conventional materials and methods. The interface between the seal and the borehole wall would remain a surface of potential weakness, it is unlikely the integrity of the materials or the seals could last for the 10^5 years or more required and the EDZ would remain as a low permeability by-pass of the seals.

To create a seal as strong and durable as the host rock and eliminate the EDZ, Gibb *et al.*[1, 4, 5] proposed an innovative sealing method in which the casing is first removed from a section of the borehole. This section is backfilled with crushed granitic host rock which is then partially melted, along with a significant thickness of the wall rock, by down-hole electrical heating before being recrystallized to a holocrystalline granite. This rock is virtually identical to (and continuous with) the host rock. The process is referred to as "rock welding" and is being researched and developed by the DBD Research Group at The University of Sheffield in the UK.

IV.A. Experimental Basis

Attrill and Gibb[10] demonstrated that at the pressures prevailing at depths of 4 to 5 km in the continental crust (~ 150 MPa) granite begins to melt at around 700°C and undergoes significant amounts of melting below 800°C under both water-saturated and water-undersaturated conditions.

They also showed[11] the melts can be cooled at rates that are quite realistic in the context of sealing a DBD to produce a holocrystalline rock with identical mineralogy to the original granite. Fig.1 shows a typical S-type granite and Fig. 2 shows a piece of the same granite that has been partially melted at 800°C for 23 days (generating over 80% melt) then recrystallized by cooling to 560°C at 0.1°C/hour before quenching. No glass (quenched melt) remains in the product, which should be compared with the lower part of Fig. 1. The mineralogy and texture are identical and the only obvious difference is the finer grain size of the recrystallized rock (note the difference in the scale of the two photomicrographs). The grain size is, of course, a function of the cooling rate which can be varied.

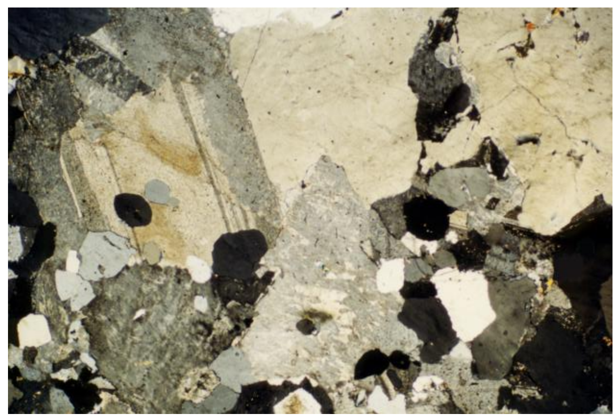

Fig. 1. Thin section of granite S93/7[10]. (Cross-polars. Field of view is ~5.5 mm wide).

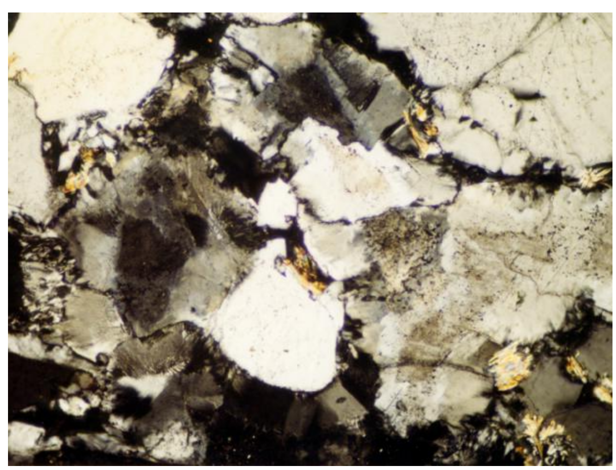

Fig. 2. Thin section of granite S93/7 after melting at 800°C and cooling to 560°C. (Cross polars. Field of view is ~ 1.2 mm wide.)

IV.B. Engineering Concept

The basic engineering concept for creating rock welded seals in DBD begins with backfilling the borehole with crushed host rock for a short distance above the uppermost waste package. This is topped with a cement plug (Fig. 3). The casing of the DZ is then cut or ground away for several meters above the plug (depending on the length of rock weld required) to expose the wall rock and the hole is flushed with clean water. About two thirds of the casing-absent section of the hole is then filled with a dense slurry of finely crushed host rock, ideally delivered down-hole by hopper rather than pumped from the surface. The solids are allowed to settle and can be compacted. A sacrificial electric heater connected to the surface by a retrievable umbilical cord is lowered on to the crushed rock and more crushed rock added to backfill the hole for several meters above the heater. Finally a pressure seal is set above the backfill (Fig. 3) to serve as a temporary 'lid' during the creation of the rock weld.

Power is supplied to the heater to partially melt the enclosing backfill and the host rock for an appropriate distance beyond the borehole wall. Although quite viscous, the silicate liquid flows into any voids while the associated supercritical fluid migrates upwards to the top of the melt zone and the heater settles slightly into the melt. After a pre-determined period, likely to be a matter of weeks, the power is switched off or reduced gradually to allow the melt to cool at a rate compatible with complete recrystallization. Depending on the grain size desired, the period of controlled cooling could last between a few weeks and a few months[11].

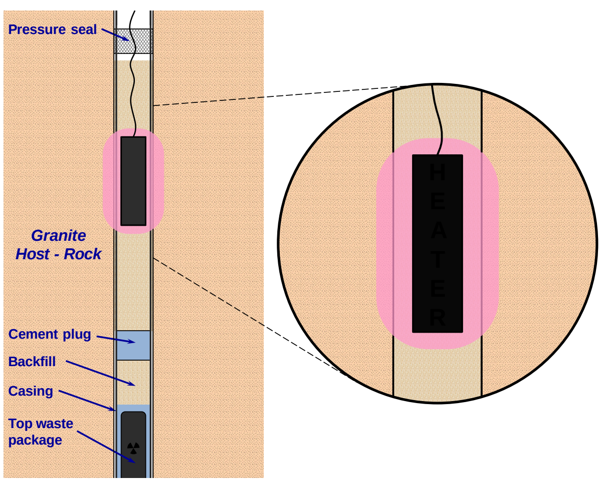

Fig. 3. Schematic of the rock welding concept for sealing a deep borehole disposal (not to scale).

IV.C. Thermal Modeling

We have undertaken heat flow modeling of various rock welding scenarios based on the above concept using a modified version of our 'in house' heat conduction code '*Granite*'[1, 4, 12]. This predicts the 3-D distribution of temperature with time in and around the heater, thus enabling evaluation of the shape and size of the weld and informing heater design and operation.

IV.C.1. Shape and Size of Rock Welds.

Fig. 4 shows an example of a rock welding scenario for a 0.66 m diameter borehole – the largest currently envisaged as practical for DBD[3], e.g., of the containers of vitrified reprocessing HLW produced at Sellafield (UK) or La Hague (France). Fig. 5 is an isotherm plot of the maximum temperatures attained in and around the borehole in this scenario. The modeling also provides information on the time taken to reach these temperatures.

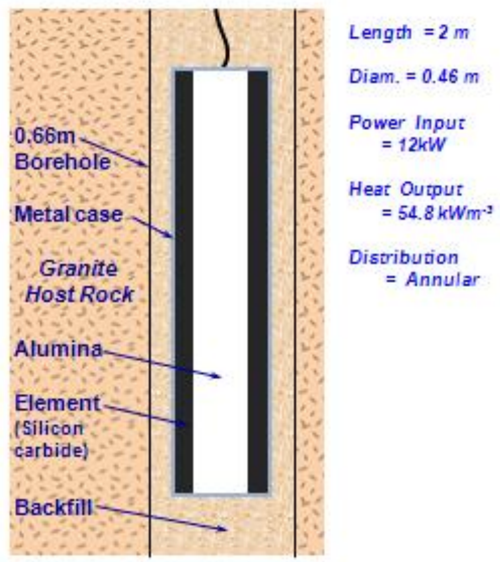

Fig. 4. Schematic of a possible rock welding scenario for a 0.66 m diameter borehole using a hollow cylindrical heater.

The 700ºC isotherm in Fig. 5 corresponds to the water-saturated solidus of the granite shown in Fig. 1 as determined by Attrill and Gibb[10] for a confining pressure of 150 MPa. Under the conditions modeled, all of the backfill and host rock inside the red line would undergo partial melting and subsequent recrystallization to create a rock weld. Outside the 700ºC isotherm the temperatures would be too low to actually melt the rock but it is worth noting that down to perhaps as low as 500ºC, they could result in the annealing of any pre-existing microfractures, e.g., 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 the heat output within the heater. However, it is evident even from the simple case shown in Figs. 4 and 5 that rock welds that would seal the borehole and eliminate the EDZ could be achieved with quite modest power inputs and on a realistic timescale in the context of DBD.

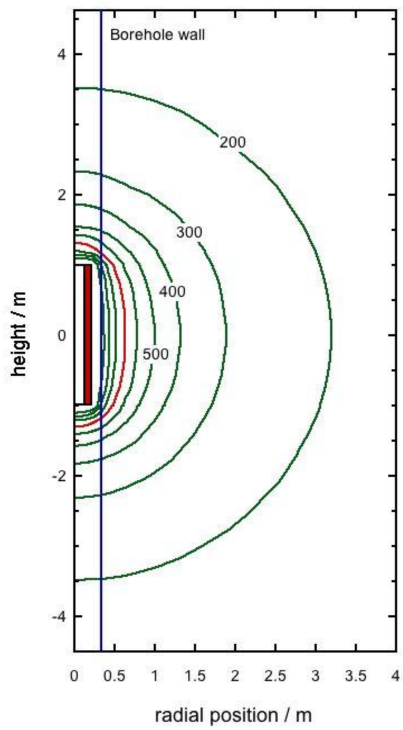

Fig. 5. Isotherms of peak temperatures generated in the scenario illustrated in Fig. 4. The 700ºC (red) isotherm corresponds to the solidus temperature for the granite shown in Fig. 1[10].

IV.C.2. Heater Design.

Clearly the heater has to be able to operate under water saturated conditions at high pressures (see below) and in potentially difficult, highly saline, conditions but there are various designs and materials that can meet these requirements.

Like the waste packages, the heater has to be lowered carefully into position down the hole. This would most easily be achieved using coiled tubing[3] with the power leads inside. The levels of power required for rock welding can be supplied by means of an umbilical cord similar to those used for remotely operated submersible vehicles, which are routinely used at much greater depths and pressures than in a DBD. Once the rock weld has solidified the coiled tubing can be detached and recovered along with the power leads leaving the heater sealed inside the volume of recrystallized granite.

There are, however, a number of challenges specific to the sealing objective that must be addressed. These include –

- Generating large enough welds to have the physical strength needed to seal the borehole for tens, if not hundreds, of thousands of years and withstand any likely tectonic stresses.
- Ensuring the welds penetrate far enough into the wall rock to eliminate the EDZ as a potential by-pass of the seal.
- Avoiding temperatures inside the heater that are unacceptably high for the materials used to construct it.
- Generating the temperatures needed to partially melt the host rock to an appropriate distance from the borehole in practically realistic times.

Heat flow modeling used in conjunction with different down-hole scenarios and heater designs should enable determination of the optimum conditions for the generation of rock welded seals for DBD.

IV.D. Role of Water

A fundamental requirement of the rock welding concept is that it must work 3 km or more down in a water-filled borehole. Hence the role of water is crucial. Separation of a discrete vapor phase (boiling) during partial melting of the granite could create a number of practical problems so the rock welding process should be carried out above the critical point of water (374ºC and 22.06 MPa). Given the amount of water likely to be in the borehole, any melting would be under water-saturated conditions leading to the presence of a supercritical hydrous phase. Furthermore, significant pressure is necessary to lower the water-saturated solidus of granitic rock to practically achievable temperatures for down-hole heating.

In a borehole open to the surface the pressure at any depth is a function of the height and density of the column of fluid in the hole. For fresh water the critical pressure would be reached at a depth of around 2.25 km. Allowing for a small margin of safety, the minimum depth at which rock welding should be attempted is 2.5 km (unless the borehole can be over-pressured). Most DBD schemes place the top of the DZ at around 3 km at which depth the pressure of the water column is about 29.5 MPa. While well above the critical pressure, this is still significantly less than the pressure at which the melting and recrystallization of granite has been demonstrated experimentally[10, 11].

The effects of lower pressures on the water-saturated phase relations of granitic rocks would be to raise the temperatures at which most changes occur and especially of the solidus and liquidus. For example, one particular biotite granite[13] that begins to melt at 700ºC at 150 MPa does not begin to melt until around 830ºC at 29.5 MPa. Raising the solidus by such an amount would have a significant effect on the % of melt generated at any given temperature and so have important implications for rock welding. Unfortunately, the effects of pressure and of variations in chemical composition on the water-saturated melting of granitic rocks are not well known for pressures below 100 MPa. Consequently once a specific site is selected for a DBD and the host lithology is defined it would be necessary to determine experimentally and quantify the phase relations for the granitic rock in question under the precise conditions at which it is proposed to carry out the rock welding. This would then enable the translation of predicted temperatures in and around the borehole to actual percentages of melting and permit customized management of the rock welding process.

V. CONCLUSIONS

Uncertainties surrounding the suitability of conventional borehole sealing methods and materials, particularly their durability and ability to seal the EDZ around the hole, necessitate the development of a better method for DBD of radioactive wastes. Rock welding is one such method. Generic experimental knowledge of granitic rocks is adequate to confirm that extensive partial melting and complete recrystallization is possible at realistically achievable temperatures and cooling rates in the context of a deep borehole. Further, heat flow modeling indicates that rock welds of sufficient extent to completely seal the borehole and eliminate the EDZ could be achieved with surprisingly modest power inputs and on a time scale quite compatible with a DBD program. All that remains to prove the concept is an accurate quantification of the melting and recrystallization of an actual host rock followed by implementation in a test borehole and verification of the strength of the seal created.

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