Borehole Construction and Operation for Disposal in Crystalline Rocks

By John Beswick

The possibility of disposing of radioactive waste in very deep boreholes has been considered for more than 50 years. A deep borehole disposal (DBD) concept was researched in some detail by the U.S. Department of Energy's Office of Nuclear Waste Isolation (ONWI) in the early 1980s and reported on in 1983 [1]. At that time, the ONWI report rejected DBD of radioactive waste on the basis that the necessary hole sizes and depths were not achievable. Since the 1980s, the technology for drilling and supporting deep boreholes has advanced dramatically, such that this is no longer true.

In recent years, the idea of DBD has been considered by a few waste management organizations, notably Svensk Känbränslehantering AB (SKB), which first reported in the late 1980s [2], and reviewed again in 2000-2001, a study on deep drilling considerations in which the author was involved. Other studies were reported by Sheffield University in the United Kingdom [3] and the Massachusetts Institute of Technology [4] in 2003. Further studies were carried out in the U.K. for the Radioactive Waste Management division of the Nuclear Decommissioning Authority (NDA) in 2008 [5].

To date, most considerations of DBD for radioactive waste have focused on a disposal zone (DZ) for the waste in the crystalline rock basement. The limited number of deep and ultra-deep boreholes drilled primarily for geoscientific exploration and engineered geothermal systems (EGS) in the basement over the last 45 years have provided much detail about the geology at depth at the locations concerned and, of particular importance for DBD, experience and information on the drilling methods and tools that will withstand the severe environment in these hot, hard, stressed, and abrasive formations.

Historically, however, there has been little demand for deep and very deep holes in crystalline rock to these depths in these formations, and no experience of drilling deep holes to 5,000 meters in large diameters. Hence the need, at this stage, to extrapolate data from experiences in deep and very deep small-diameter holes and large-diameter drilling technology used for mining applications. This contrasts with the vast amount of data that is available from the many thousands of deep wells drilled in the oil industry, but drilled mainly in sedimentary formations.

A deep borehole for radioactive waste disposal comprises two fundamentally different stages. The first is the borehole construction itself, which, as in all deep drilling, poses risks. While these risks may give rise to troublesome situations during drilling, they can usually be remediated. Once the borehole has been successfully drilled, the status changes and the borehole becomes a radioactive waste facility. Hence, the second phase, comprising the waste emplacement and final sealing, must have a very high level of guaranteed success or an extremely low probability of failure. This unusual requirement for deep boreholes must pervade the design and execution of all the activities related to such a project.

Site selection

Granitic basement rock at suitable depths for DBD underlies much of the continental crust. Experience over the last 45 years in geoscientific and geothermal energy boreholes provide considerable data on drilling in granitic rocks. While very different from the geological conditions generally encountered in the oil and gas industry, this data 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. Any sedimentary cover, however, should be easy to drill, relatively stable, and ideally include one or more impervious natural barriers to vertical fluid flow. Selection should also identify a stable formation throughout the proposed DZ. Boreholes should be sited to avoid abnormally geopressurized zones, potential hydrocarbon provinces, mineral resources (as indicated by surface and known expressions of economic mineralization), likely geothermal energy prospects (high geothermal gradients), and other subsurface resources likely to attract attention in the future and therefore be liable to human intrusion.

The choice of geological setting is important. The ideal location should be such that the crystalline basement is at about 1,500 m to 2,500 m below the surface. Boreholes could be drilled in an outcropping granite intrusion or basement from surface, but an overlying sedimentary sequence has advantages in the upper-hole sections, as it may be easier to drill in the large diameters required. These relatively large-diameter wells, however, need to have competent rocks throughout the sequence to minimize problems during drilling, casing, and sealing. The presence of thick salt horizons could be an advantage due to their mobility and sealing properties, but this requires extra-strength casing through those intervals, which will be heavier to install and may need larger-diameter boreholes.

A younger, intrusive granite may be favored over an older granite complex, as the characteristics are more likely to be consistent and less likely to include a variety of historical structural and lithological changes that can make drilling more difficult and large breakouts more likely. Such formations, however, are generally hotter than the basement at the same depth due to the remnant radiogenic decay of thorium, uranium, and potassium.

As deep wells will experience stress-induced enlargements, or "breakouts," due to the horizontal stress anisotropy, sites where a significant principal stress difference occurs should be avoided if possible, as these potentially will be more prone to borehole elongation and the development of a large stress-relaxation zone around the borehole itself. The degree of stress breakout varies depending on the hole size, rock strength, the degree of anisotropy of the three principal stresses, and the rock-mass quality in terms of the presence, orientation, and distribution of discontinuities and their infillings. It is also time-dependent.

Examples from previous drilling projects illustrate that the borehole at depth is more likely to be of an irregular, generally oval shape with a larger hole volume than the nominal drilled dimension. The extent of overbreak depends on the stress regime and time elapsed since the interval was drilled. Moreover, the area surrounding the borehole will experience stress relaxation as the confining pressure on the rock is reduced, creating a potential pathway for fluid migration in this disturbed zone. Some mitigation may be achieved by increasing the composition and density of the drilling fluid, but this is unlikely to be a significant mitigation.

Borehole construction

Construction of the uppermost two large-diameter intervals may require a system of blind shaft drilling and casing as commonly used for mine shafts (Fig. 1). A 2008 report for the NDA includes a review of some of the blind shaft drilling achievements over the previous 50 years [5].

Large-diameter casings present issues related to

Fig. 1. Shaft drilling rig. (Courtesy of Shaft Drillers Inc.)

Fig. 2. New concept automatic drilling rig. (Courtesy of H Angers Söhne)

weight and to collapse strength, which give rise to installation issues and also limit cementation pressures. Shafts are normally drilled by reverse circulation. Blind shaft drillers use steel or composite casing comprising steel and concrete, and sometimes concrete linings. The composite casing has much better collapse resistance, allowing them to be floated into the borehole with minimal surface load. The installation, however, is more time-consuming due to the need to weld the relatively short segments of casing together.

Blind shaft drilling is being used more and more for shaft sinking as an alternative to the more traditional mining techniques. The process is well-developed and highly automated. Typically, large-hole drilling requires only a three- or four-man crew. For mining applications, depending on the geological conditions encountered, the drilling process normally advances at much quicker rates than a conventional shaft-sinking operation.

Cementing of large-diameter steel casings can be achieved with guide pipes welded to the outside of the casing with a tremie placement system, allowing the casing to be cemented in stages to avoid overpressure and casing collapse. This approach needs a larger annulus than would otherwise be required for the use of oilfield cementing methods.

For the lowermost intervals, a traditional oilfield approach using a heavy drilling rig, large-diameter drill pipe, and appropriate gauge protected bits, stabilizers, and reamers is applicable. In the severe environment of the crystalline basement, roller stabilizers and roller reamers with heavy-gauge protection are generally necessary. In recent years, there have been a number of innovations with oilfield drilling rigs, with the introduction of more mechanization and automation, and new concept rigs aimed at improving safety (Fig. 2).

Another approach to the surface interval is to mine the top 250 m to 500 m using a mechanized vertical shaft-sinking machine [6]. This would allow the construction of a final abutment deep underground using asphalt or other natural, impermeable materials. This concept was considered in the report for SKB in 1989 [2]. While largely cosmetic in the context of the DBD concept, such construction affords a final seal to the biosphere and offers an approach that may help in the issue of public acceptance.

The smallest shaft that can be constructed using this method at present is about 4.5 m in diameter. When the shaft is dewatered and pumped dry, however, this construction would allow personnel access for the final abutment construction and any supplementary annular pressure grouting of the uppermost support-lining segments if necessary, followed by plugging the hole with appropriate materials above the abutment. If a large-diameter surface hole of this kind were considered, a guide and support system would be necessary by use of a removable technical casing through the shaft to allow drilling to continue below.

Verticality control

Experience has shown that for any deep or very deep borehole, it is essential to maintain verticality to minimize doglegs, tortuosity, and uncontrollable deviation due to stress breakout. Such technology was not available for many of the deep and very deep wells drilled prior to the mid-1990s. These systems were largely developed for deep-hole drilling during the KTB super-deep scientific drilling program in Bavaria, Germany, in the early 1990s [7]. The tools developed for that project were used to a depth of about 7,200 m, where the maximum allowable temperature of 175° C was reached, which was the limit for the electronics. At this depth, the horizontal displacement was only 12 m. The well then deviated to the northeast, with the final displacement being some 300 m [8, 9].

The development of proven vertical drilling systems offers a method of maintaining verticality in drilled boreholes. For larger hole sizes, however, a pilot hole may have to be opened with appropriate bits and a hole-finder used to follow the vertical pilot hole. This system is now routinely used in blind shaft drilling. Down-hole, motor-driven vertical drilling systems are now available, although there may need to be some development of large-diameter tools so that the lowermost intervals could be drilled with these devices.

Cementing and sealing

Oilfield cementing has been practiced for more than 100 years. Oilfield and geothermal cementing is the process of mixing a slurry of cement, additives, and water and pumping it down through steel casing and into the annulus through a cementing shoe or bypass valves in the casing to form a cement sheath in the annulus between the casing and the formation. Due to the nature of a compound that sets quickly, failure is a serious problem in that if a problem occurs during the cementing operation, unless the cement can be washed out quickly to repeat the operation, the cement that has been placed sets and cannot be removed.

These operations are often referred to as "primary cementing" and "remedial cementing." The fact that remedial cementing is required from time to time, and is a major subtopic of any literature on the subject, emphasizes the problems that are associated with obtaining good cement competence, distribution, and annuli isolation. The two principal functions are to restrict fluid movement in the annulus to form a seal that provides isolation between formations and from the surface, and to bond and support the casing to the rock formation. The technology is not so complex in principle and is well-documented.

In considering how to seal and close these deep boreholes for radioactive waste disposal, it is important to recognize the starting point. The borehole construction and post-drilling waste disposal seals need to be considered as a system, whereby the actual construction of the various stages of the borehole forms part of the constituent elements in developing the sealing and isolation of the system.

Verification of the success or otherwise of cementing using traditional oilfield procedures, or what are generally known as "cement bond logs," is also fraught with complexities. This is particularly so in large diameters, where the signals by which the various integrity tools are interpreted are so attenuated that the results are of poor quality and sometimes misleading.

Cementitious compounds can be effective if successful placement is achieved, and they can maintain a reasonable life span as a seal. Of course, there are no data to predict the lifetime of a seal formed of cementitious material, as used in the various forms for oilfield or construction projects (e.g., shafts and tunneling), in the context of the time span required for radioactive waste containment. In terms of, say, a 100,000-year model, only materials occurring in nature can demonstrate stability and/or sealing properties over such a long period. Such materials include the rocks themselves, bentonite, salts, bitumen, and asphalts. However, these cementitious seals placed during drilling, by whatever placement method is adopted, can only be considered as temporary in the timescale of potential radionuclide migration. The time that they are effective, however, may be sufficient to cover the period of the thermal high arising from radioactive decay of the wastes.

It is assumed that the host rock itself, in its virgin state, together with the groundwater salinity gradient, will form an adequate containment. That is the principal concept of and argument for deep borehole disposal. The presence of a sedimentary sequence including clays and/or a thick salt horizon above the crystalline basement would be an advantage in providing an impermeable aquiclude to add to the containment system. The concept of creating a quasi-granitic seal horizon or horizons by rock welding [10] above the DZ can provide the long-term solution, such that the borehole itself and any disturbed or relaxed zone around the borehole is permanently sealed, returning a zone above the DZ to the same, if not better, host rock characteristics as occurs in nature.

Borehole operation

In a paper by Beswick, Gibb, and Travis [11], coiled tubing (CT) was suggested as the preferred option for placement of waste canisters in a deep borehole. This method is suitable for single canisters weighing some 5,000 kilograms and is preferred as it simplifies the surface connection to the canister, eliminates the need for canister-to-canister connections, and minimizes the surface shielding requirements. Single-canister emplacement also eliminates any tortuosity concerns in the borehole due to the small clearance between the inside diameter of the casing and the canister itself.

A key technical issue with CT is the life of the coil of steel tube. CT is now manufactured in endless steel tubing, which has eliminated the welded sections that were used in the past. Fatigue is generally the major factor in determining the working life of a CT string. The deployment and retrieval of the continuous tubing requires that the tube be subjected to repeated bending and straightening, commonly referred to as "bend-cycling."

The amount of strain imposed upon the tube body during the bend-cycling process is considered to be enormous, in many cases of the order of 2-3 percent. When subjecting the CT to this type of fatigue cycling, the stress and/or strain fluctuations to failure can be estimated using conventional axial fatigue-life prediction approaches. The service providers have developed sophisticated software and instrumentation to monitor and determine the safe life of the tubing, such that the CT is taken out of service before there is any risk of failure. Failure is now a rare event.

One key question is how many trips can be made with a CT unit before the coil has to be discarded. A review of several scenarios for single waste package deployment has shown that more than 100 round trips can be made with one coil before it needs replacing. However, the replacement cost is modest compared with other operational costs.

Notwithstanding the fact that tube fatigue occurs, the use of CT for the deployment of waste canisters is considered to be the best option. Putting the use of CT into context, in 2015 there were more than 2,000 units operating worldwide, and coils of close to 10,000 m were deployed. Diameters of tubes range from 25 mm to 114 mm.

Although the waste packages can weigh something on the order of 5,000 kg [11], it may be necessary to include some form of sinker or tension weight in the assembly for the CT retrieval. This must be considered in any rigorous analysis. Also, the connection and release mechanisms have to be designed to suit this particular case. Release mechanisms are already available, usually using a dropped ball and pressuring the string to shear pins. An electrical system also could be feasible, which would need conductors through the CT, a feature now available. This latter option also would allow accurate depth monitoring against a marker at a prescribed depth in the casing at the top of the DZ, rather than rely on the surface counter for depth determination.

The use of CT for the deployment of radioactive waste canisters is therefore entirely feasible, and existing equipment is available. Other than the surface shielding arrangements, the only special design would be the canister pickup and release mechanism.

Conclusions

While DBD offers new challenges for the deep drilling industry and the need for the development of some new technology, it is considered that a deep borehole system can be designed and constructed to fulfill the requirements of radioactive waste disposal, ensuring that the waste is isolated from the biosphere to a degree that a robust safety case can be demonstrated.

There is a strong case for a slim investigation borehole to characterize the geology and hydrogeology and to allow relevant evaluation and testing at a potential location. If such a borehole is located close to an eventual waste disposal borehole(s), however, the plug and abandonment (sealing) must be to the same standards as in the larger-diameter disposal borehole to eliminate any additional direct pathways for radionuclides to reach the biosphere. Therefore, the sealing and isolation of the investigation borehole must adopt the same systematic approach as for the waste disposal borehole.

In any demonstration or early disposal, time and cost should not be a priority. An environment for innovation and engineering is important and must be encouraged. Value engineering comes later after the concept is proven by a full-scale demonstration and successful early disposal of actual waste.

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