Views on Long-Term Safety of Deep Borehole Disposal – 16657

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ABSTRACT

The Swedish Nuclear Fuel and Waste Management Co., SKB, has since the end of the 1980s evaluated Deep Borehole Disposal (DBD), of spent nuclear fuel (SNF). This has been done in parallel with the development of a mined repository concept based on the KBS-3V method. The most recent evaluation involved a broad comparison between the KBS-3V method and DBD. The comparison highlights differences between the two methods in the whole chain of the SNF handling including premises for siting, licensing, repository construction, safety during the operational phase, post-closure safety, physical protection, nuclear safeguards, retrieval of the deposited SNF, time planning, need for development, costs and non-technical project risks. The ambition has been to make an as objective comparison between the two methods as possible, bearing in mind that there are big differences between the two concepts in terms of technical maturity as well as in terms of both quantity and quality of available data.

While the primary safety function of the KBS-3V method is long-term containment in a corrosion resistant copper canister, the safety of DBD relies on stagnant groundwater at depth. It is argued in the aforementioned study that this groundwater stagnancy may be jeopardised because of heat and gas evolution in the disposal boreholes, and that deformation of the boreholes make efficient sealing of the deposition boreholes difficult. SKB has taken the position that the DBD method is associated with too many question marks to make it interesting as an alternative method in the Swedish programme.

INTRODUCTION AND BACKGROUND

Disposal of radioactive waste in several kilometres deep boreholes has been discussed since the infancy of nuclear power in the 1950s. During the 1970s the concept was evaluated together with a wide variety of high-level waste (HLW) disposal alternatives [1] and in 1983 the consulting company Woodward-Clyde addressed engineering issues related to deep borehole disposal (DBD) suggesting disposal in 50 cm wide and 6 km deep boreholes [2].

The Swedish Nuclear Fuel and Waste Management Co.'s (SKB's) involvement in DBD started in 1987 with an assessment of the feasibility of the concept and a cost analysis that was published in 1989 [3]. In the study a design concept based on 80 cm wide and 4 km deep boreholes was used. This concept was further evaluated together with a couple of mined repository concepts in the subsequent PASS project (Project Alternative Systems Study) that was finalised in 1992 [4]. The study was concluded by a ranking of these concepts based on technical feasibility, long-term performance and safety, and costs in which DBD came last. In 2000 SKB published a report [5] on the feasibility of drilling 80 cm wide holes down to 4 km depth as suggested in earlier SKB studies. The study recommended development of percussion drilling technology with foam transport of cuttings, in order to enhance drilling efficiency.

In 1998 SKB published an appraisal of geoscientific data of relevance to DBD [6]. Updates on the geoscientific knowledge of conditions at great depths were published in 2004 and 2013 [7, 8]. SKB in 2000 estimated that it would take a 30-year programme costing about 4.2 billion Swedish kronor to bring the scientific and technological knowledge about DBD to a level that would allow a true comparison with a mined repository [9].

SKB has expressed a commitment to follow and evaluate the international development of DBD. This has resulted in two studies in which DBD was compared with the KBS-3V[1] method. The first of these comparisons [10] was based on the design concept developed for the PASS project. An update of the comparison based on a slightly modified version of the reference design developed by Sandia National Laboratories (SNL) [11] was published in 2014 [12]. The current paper is based on the SNL study.

The comparison comprises a broad spectrum of topics including premises for siting, licensing, repository construction, safety during the operational phase, post-closure safety, physical protection, nuclear safeguards, retrieval of the deposited fuel, time planning, need for development, costs and non-technical project risks. Although the ambition has been to make an as objective study as possible, it is evident that the comparison is influenced by the fact that the maturity of the two concepts compared differ. This paper focuses on post-closure safety.

CONCEPTS COMPARED

Description of the Concepts

The comparison is made between disposal of spent nuclear fuel (SNF) in a mined repository based on the KBS-3V method and disposal in deep borehole. Figure 1 illustrates the barriers built into a KBS-3V repository. The SNF is encapsulated in corrosion resistant copper canisters with iron inserts designed to sustain external loads. The canisters are deposited surrounded by compacted bentonite in boreholes in the floor of tunnels at a depth of about 500 m in crystalline rock. The tunnels are then backfilled with suitable clay materials.

The post-closure safety of the KBS-3V method has been analysed in several comprehensive safety assessments both in Sweden and in Finland. The latest assessment in Sweden, the SR-Site study [13], was included in SKB’s applications for licenses to construct, own and operate a repository at the Forsmark site. In the same way the latest Finnish assessment, TURVA 2012 [14], was included in Posiva’s

[1] The KBS-3 method includes two canister emplacement modes/concepts; single canister in a vertical hole (KBS-3V), and multiple canisters in a horizontal borehole (KBS-3H).

application for a construction license for a SNF repository at the Olkiluoto site, which was approved by the Finnish government on the 12th of November 2015.

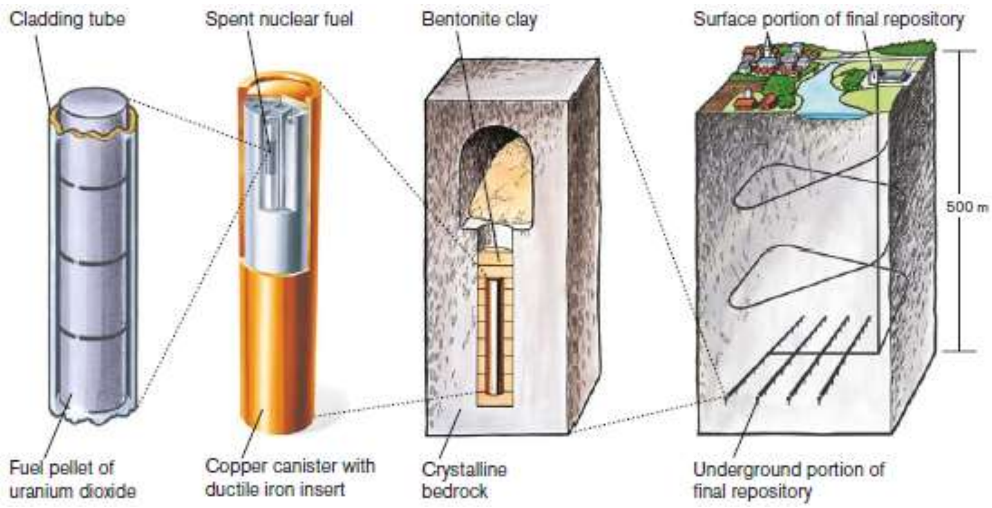

Fig. 1. Barriers in a repository based on the KBS-3V method.

The conceptual DBD design used in the comparison study is illustrated in Figure 2. The design is a slightly modified version of the reference design published by SNL [11] with a wider borehole [15]. The reason for the design modification is that it allows wide enough canisters to host two BWR fuel elements without dismantling and consolidation of the SNF.

Dismantling the amount of SNF foreseen to be generated in the Swedish nuclear power programme would involve remote handling of in the order of five million SNF rods, some of which can be swollen or slightly deformed after the in-core period. Also, the dismantling will leave large amounts of radioactive metal scrap like top and bottom plates, grid assemblies and fuel channels that will need to be managed. A decision was taken not to assume fuel dismantling and consolidation as this would potentially give rise to significant personnel doses and would require a facility for remote handling with not insignificant technical risks. Since canisters in the reference design developed by SNL would allow only one BWR fuel element without consolidation and the Swedish programme predominantly generates spent BWR fuel, it was decided to widen the borehole by about 13 mm (from 17 to 17½ inches) to allow the use of a canister that would instead host two BWR fuel elements.

It was assumed that the canisters were stacked in the borehole in the depth interval 3 – 5 km. In accordance with the procedure suggested in [11] and [15], the canisters were assumed to be joined together in about 200 m long strings of 40 canisters each. The strings were separated by bridge plugs and 10 m long concrete plugs carrying the weight of the canisters above. Each hole can host 10 such canister strings.

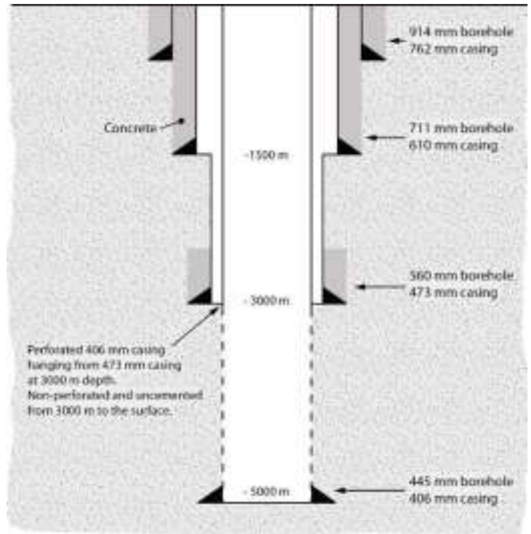

Fig. 2. Conceptual borehole design for deep borehole disposal of spent nuclear fuel.

During emplacement of the canister strings the hole will be equipped with a constant diameter guide tube all the way from the surface to the bottom, in order to ascertain free passage of canisters. In the disposal depth interval, i.e. the disposal zone, the guide tube or casing was assumed to be perforated in order to avoid buckling from the hydrostatic pressure on the outside and to allow the mud in the bore hole to fill the annulus between the casing and the borehole wall. After emplacement a 100 m long concrete plug would be cast above the disposal zone. The guide tube would be cut above this plug and pulled out of the hole. Also the 473 mm diameter casing above the disposal zone, see Figure 2, would be cut above the cemented section and pulled out of the hole leaving the borehole section between 1,500 m and the top of the disposal zone uncased thus allowing good contact between sealing features and the wall of this part of the borehole.

Differences in Important Safety Functions

The two concepts compared have very different safety characteristics. Figure 3 illustrates the engineered barriers in the near field for the two repository types. The figure illustrates the amount of BWR fuel that can be encapsulated in one KBS-3V canister, i.e. 12 BWR elements.

In the KBS-3V repository one copper canister will be emplaced in an about 10 m deep borehole located in the floor of a tunnel. The canister will be surrounded by pre-fabricated and pre-emplaced blocks of highly compacted bentonite that will swell upon wetting creating a plastic low permeability gel around the canisters. This gel will protect the canister by preventing chemical agents in the groundwater from reaching the canister surface and, in addition, by buffering against some rock movements.

In the DBD concept it will be difficult to pre-emplace low permeability buffer material around the canisters. It has been suggested to use pre-fabricated packages with canisters surrounded by compacted bentonite held in place by perforated metal cassettes similar to the clay seals suggested for the sealing of investigation boreholes in the KBS-3V method [16]. However, as illustrated in Figure 3, there is very little space in the borehole for such bentonite overpacks. Also, the canister with the overpack would have to travel between 3 and 5 km through a hole filled with water or drilling mud before it reaches its final destination. It is not unlikely that this will cause material losses from or deformation of the overpack. Because of this it was assumed that the borehole was filled with drilling mud when the emplacement is carried out and consequently that chemical agents in the groundwater relatively easily can reach the canister surface.

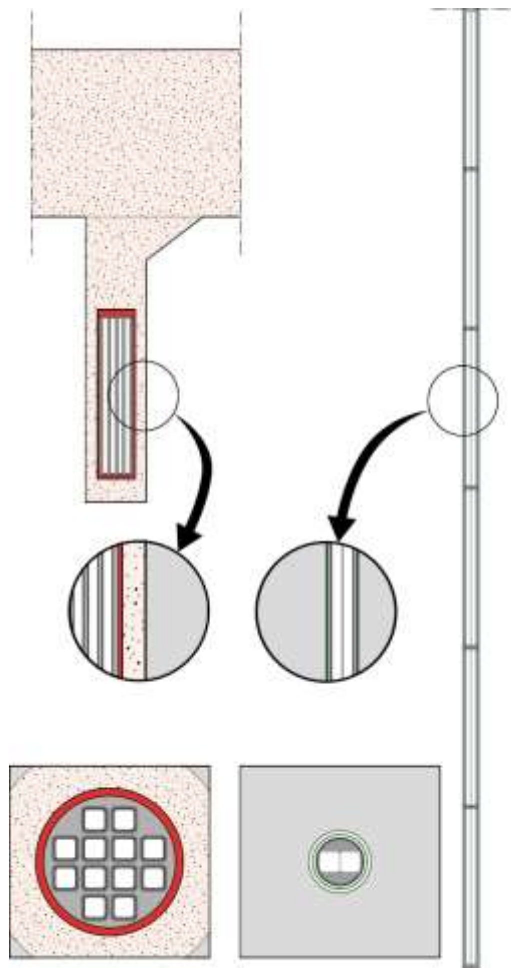

Fig. 3. Disposal of 12 BWR fuel elements in a KBS-3V repository (left) and in a deep bore hole (right) respectively. The two concepts are drawn to scale.

As a consequence of the described differences in the near field design between the two concepts, the reliance on the engineered barriers will differ strongly when defining a safety case. Central in the safety case are the safety functions of the barrier system.

The primary safety function of the KBS-3V method is the containment of the radionuclides in the SNF in a corrosion resistant copper canister protected by a long-term stable bentonite buffer with low permeability [13]. If the barrier function of the copper canister is somehow broken, the secondary safety function of the KBS-3V method is the radionuclide retardation provided by the bentonite buffer and the geological barrier.

In the case of DBD the primary safety function will be the very slow groundwater flow at great depths supported by a combination of low permeability rocks and density stratification of the groundwater due to higher salinity at depth [3, 6, 7, 8 12]. It has been suggested that, in particular, the density stratification would provide almost total containment of any radionuclide released into the groundwater. The secondary safety function would then be the same as in the KBS-3V method, i.e. retardation during migration through the rock.

Likely Post-Closure Evolution of the KBS-3 Method

As mentioned above, the primary safety function of the KBS-3V method is the long-term containment in the corrosion resistant copper canister that, in turn, is protected by the bentonite buffer in a crystalline rock providing favourable chemical, hydrogeological and mechanical conditions. During the past 30+ years, the safety of the KBS-3V method has been thoroughly analysed in several safety assessments. In the most recent assessment, SR-Site [13], three potential canister failure modes were identified: *i)* corrosion of the copper shell of the canister, *ii)* shear loads on the canister and *iii)* isostatic loads.

Under the reducing conditions that are expected to be restored shortly after closure of the repository, the only significant copper corroding agent in Swedish granitic groundwater is sulphide giving rise to a corrosion reaction that for simplicity can be written as illustrated in Equation 1 (non-stoichiometric forms are possible):

$$2Cu + HS^- + H^+ \rightarrow Cu_2S + H_2 \qquad \text{(Eq. 1)}$$

The assessment has demonstrated that canister failure can be ruled out as long as the compacted bentonite buffer is in place and protects the canister. The bentonite gel is stable in normal granitic groundwater. However, in water with low ionic strength, the bentonite can form colloids that can be transported away by the groundwater, thereby eroding the buffer and thus leaving the canister less protected. Such conditions may occur after extended periods of temperate climate or during glacial conditions. Conclusions from statistical analyses of the groundwater flow and the sulphide concentration are that the likelihood that no canister fails during the first 1 million years is about 50% implying that the likelihood that at least one canister fails also is about 50%. The analyses also show that it is only when the highest flow rates are combined with the highest sulphide concentrations throughout the 1 million year assessment period that failure can occur [13].

Canister failures due to shear loads may occur as a consequence of large earthquakes in the vicinity of the repository. Such earthquakes are rare in Sweden but cannot be excluded over a glacial cycle. The risk for large shear movements is greater in large fractures. Means are taken to counteract such risks by avoiding disposal in positions near such large fractures. The estimated likelihood that at least one canister fails due to shear loads during the 1 million years assessment period is 10% [13].

Enhanced isostatic pressure can occur as a consequence of a glacier covering the repository area or due to swelling of the bentonite buffer. These loads have been estimated, and the canisters have been designed to sustain them. The analyses in SR-Site [13] showed that no canisters are expected to fail due to isostatic load.

Likely Post-Closure Evolution of the DBD concept

No comprehensive, site-specific, performance or safety assessment of the DBD concept has been performed up to now. As mentioned above, a consensus has developed that the primary safety function of this concept would be groundwater stagnancy due to density stratification and low permeability in the rock. The reference design [11] includes mild steel canisters with a wall thickness of about 3 cm. In the modified Swedish reference design, canisters with a wall thickness of 12 mm were assumed.

In the warm, saline and oxygen-free water at the depth of the Swedish disposal zone the canisters will corrode primarily by reacting with water under formation of magnetite and hydrogen [17], as illustrated in Equation 2:

$$Fe + \frac{4}{3} H_2O \leftrightarrow \frac{1}{3} Fe_3O_4 + \frac{4}{3} H_2 \qquad \text{(Eq. 2)}$$

The corrosion rate of mild steel is normally in the order of 10 μm/year. In the environment foreseen in the disposal zone the rate has been estimated to be about 60% of the rate measured under ambient conditions [17]. With the material thicknesses quoted above the canisters can be expected to be penetrated in about 1,000 years. However, well before that time the canisters will have lost their initial strength and started to collapse beginning at the bottom of the string that is exposed to the about 60 tons weight of the stacked canister string. Therefore, it would seem appropriate to assume that part of the radionuclide inventory in the SNF will start to dissolve in the surrounding groundwater after some hundreds of years.

Future Repository State

Figure 4 illustrates the likely future consequences in terms of radionuclide content in the groundwater due to the evolution of the repository near fields described in the preceding sections. No radioactivity dispersion is expected from the KBS-3V repository because the canisters are expected to be intact even in a time perspective of several 100s of thousand years. In the case of DBD radioactivity leakage can be expected to start within some hundred years. Due to thermal convection and gas evolution vertical transport in the borehole will distribute the radioactivity along the hole. Also, some horizontal migration of the radionuclides into fractures in the surrounding rock may take place due to a combination of diffusion and slow groundwater movement.

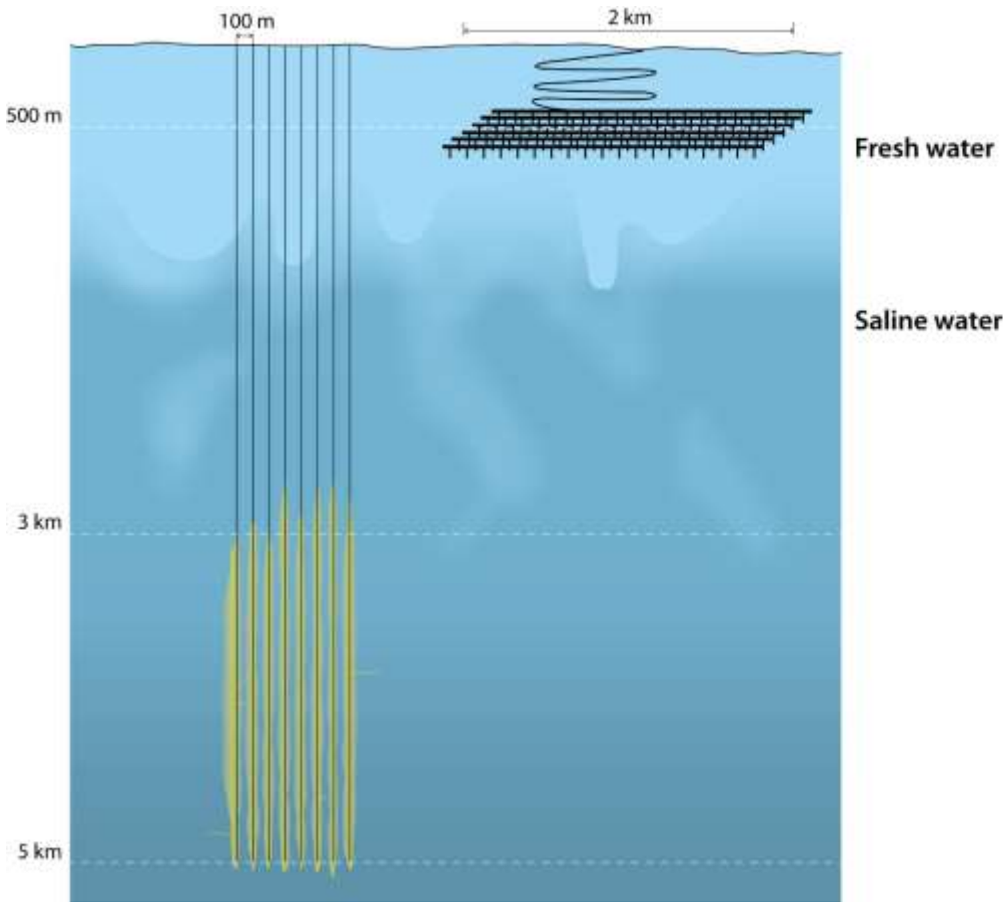

Fig.4. Likely future situation in deep boreholes (left) and in a KBS-3V repository (right). The yellow colour illustrates the extent of the radionuclide content in the groundwater. Some features in the picture are not to scale.

PERTINENT SAFETY-RELATED QUESTIONS FOR DBD

As mentioned above, the main safety function of a DBD repository is containment of radionuclides at the disposal depth due to groundwater stagnancy caused by density stratification and low permeability. Given the foreseen evolution of the near field described in the previous section, it can be argued that this containment is crucial for the post-closure safety of the DBD concept.

A normal procedure in safety assessments is to challenge the principal safety functions. In the case of DBD and its possible application in Sweden, this includes posing the following questions:

- Can a sufficiently large area with a density stratification at a suitable depth be found and will such density stratification be stable over time?

- Does the DBD repository affect the stability of the density stratification?
- Can borehole sealing be efficient as a measure against possible vertical radionuclide transport?

The current knowledge of geology, hydrogeology and hydrochemistry at several kilometres depth in crystalline bedrocks, see e.g. [6, 7, 8], have shown that there are big knowledge gaps. The questions posed above are addressed in the subsequent text based on current knowledge.

Availability and Long-Term Stability of Density Stratified Groundwater

There are indications that groundwater at depth has a significantly higher salt content than more superficial groundwater. However, there is only a limited number of boreholes extending down to these depths and, as pointed out in [18], the practical challenges that have to be dealt with, in order to get good quality data, are significant. In the comparison between the KBS-3V method and DBD [10, 12] a model for the salinity distribution in Swedish bedrock originally developed by Juhlin et al. [6] was applied, see Figure 5. The model was developed based on the following four boreholes Gravberg 1 (6,957 m deep, central Sweden), KLX02 (1,700 m deep, south-eastern Sweden), Böttstein (depth 1,500 m northern Switzerland) and RH-12 (depth 2,194 m, south-eastern England).

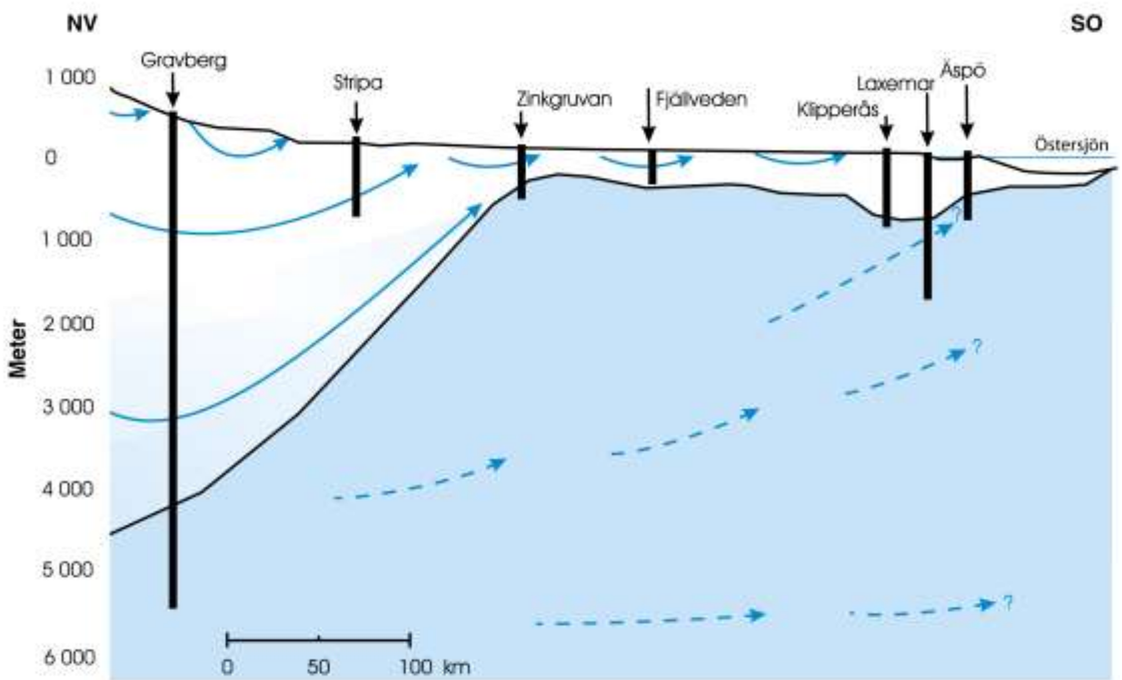

Fig. 5. Model for the distribution of saline groundwater along a vertical NW-SE cross section through central Sweden. Darker blue colour indicates higher salinity. Approximate projections of boreholes onto the cross section have been indicated by vertical black lines.

According to the salinity model a halocline appears to exist at about 1 km depth in the flat areas along the Swedish east coast. The superficial fresh water is a dilute solution with a salt content dominated by sodium salts. The deep water is a calcium salt dominated brine with a salinity of 100 – 150 g/l total dissolved solids (TDS). Further inland in areas with a more pronounced topographical relief meteoric water seems to infiltrate deeper. At the site of the Gravberg-1 borehole the salinity increases gradually from in principle fresh above about 2 km to highly saline (100 - 150 g/l TDS) at about 4.5 km.

Even though the quoted salinity model was based on few and geographically dispersed boreholes, the general characteristics have not been contradicted by later observations. In a 2.5 km deep scientific borehole in Outokumpu in Finland the salinity increased from dilute at 1.5 km depth to about 50 g/l TDS at the bottom of the borehole. In another 2.5 km deep borehole drilled within the Swedish Scientific Deep Drilling Programme (SSDP), and located near Åre in the Scandinavian Caledonides the groundwater was characterised as fresh along the length of the hole. The salinity has been studied also in the Swedish and the Finnish programmes for siting of a SNF repository. The interpretations made in these programmes are that there is a transition zone from fresh to saline water that extends from 600 – 700 m down to 1 – 1.5 km depth.

The saline groundwater in the Swedish crystalline bedrock is influenced by infiltration of meteoric water and by land uplift due to post-glacial rebound. These phenomena have been extensively modelled within the Swedish and Finnish nuclear waste management programmes. The models used have been calibrated based upon observed hydrochemical data. The models have in general demonstrated that the current situation is a result of infiltration during different episodes in the climatic and geological history of glacial melt water, marine water, lacustrine water and meteoric water.

Influences from the Repository

In the DBD repository concept the borehole itself and the surrounding rock affected by the drilling constitute a potential migration path for groundwater transportation of the dissolved radionuclides. In order for such migration to happen, the repository must create driving forces for vertical transport that are strong enough to overcome the stagnancy due to density stratification. The heat produced by radioactive decay in the SNF has been identified as a source of thermal convection in the borehole [19, 20, 21]. Another potential driving force for vertical transport in and around the boreholes is formation of hydrogen due to corrosion of canisters and casing tubes.

Modelling has shown that the thermal output from the SNF can create a slow upward flow in and around the borehole [21]. If the permeability in the borehole and the disturbed zone around the borehole affected by the drilling is high enough, thermal convection could lead to radionuclide leakage to more superficial groundwater. Consequently, the reference design presented in [11] includes permeability constraints on the sealing measures planned to be installed in the part of the borehole above the disposal zone.

In the DBD reference design [11] the canisters and the casing tubes are assumed to be made of mild steel. Under oxygen free conditions, iron will react with water to form hydrogen and magnetite, see Equation 2 above. The hydrogen formation process has been analysed and the amount formed has been estimated for the conditions prevailing in the assumed disposal zone of the borehole [17]. The conditions are non-ideal with a hydrostatic pressure in the disposal zone of the borehole that varies in the range 20 – 50 MPa, a salinity of the groundwater that can be assumed to be 100 – 150 g/l TDS and a temperature in the order of 100 ^{o}C. Under these conditions the equilibrium hydrogen pressure for the corrosion reaction in Equation 2, i.e. the pressure when the reaction halts, has been estimated to 108 MPa [17]. As this equilibrium pressure significantly exceeds the hydrostatic pressure in the borehole, it is concluded that the corrosion will progress until the iron is consumed.

The hydrogen formed as the corrosion progresses will result in build-up of a hydrogen pressure in the borehole. When the hydrogen pressure equals the hydrostatic pressure bubbles will start to form on the metal surfaces displacing the borehole liquid into the adjacent rock. When the bubbles become large enough buoyancy forces will detach from the metal surface and the bubbles will strive to move upward in the borehole and in the fractures in the surrounding rock. As the bubbles rise they will expand due to the reduced hydrostatic pressure and new bubbles formed higher up in the borehole will be added. The consequence will be an accelerating gas flow in and around the borehole.

The far from equilibrium corrosion rate has been assumed to be 10 μm/year [17]. When the hydrogen pressure increases, the rate of the corrosion reaction will be reduced. It is estimated that the corrosion rate is reduced by about 40% compared with the far from equilibrium rate [17]. The consequent rate of hydrogen formation has been estimated to create hydrogen bubbles within 1 – 5 years and to correspond to the void volume of the disposal zone in slightly more than 100 years [17].

The consequences of the hydrogen formation have not been analysed quantitatively. The conceptual description of the transport of hydrogen through the borehole and the adjacent rock should include the rise of expanding and potentially coalescing bubbles of hydrogen in a non-Newtonian drilling mud. A computational fluid dynamics model could possibly be set up for a very simplified version of such a conceptual model. From the analysis done, it appears likely that hydrogen generation could create a driving force threatening the containment provided by the density stratification of the groundwater.

Sealing Needs and Challenges

As mentioned in the preceding text the reference DBD design [11] includes constraints on the permeability of the sealing based on the results from modelling thermally induced vertical flow. The hydrogen generation discussed in the previous section is another and potentially more powerful driving force for vertical transport that would put stringent requirements on the borehole sealing measures. There is thus a need to seal the borehole and the safety functions may be jeopardised by insufficient sealing.

As mentioned before, rock stresses are likely to deform the borehole and create so called breakouts. This is illustrated in Figure 6. In order for sealing measures to be efficient, they need to fill out the fissures in the affected zone around the borehole. The sealing measure must be designed such that they can be put into place remotely through a borehole that is water filled and there will be no way to check that the measures are efficient. As a consequence, the likelihood that there will be channels available along the borehole where hydrogen and potentially contaminated water can be transported will be significant.

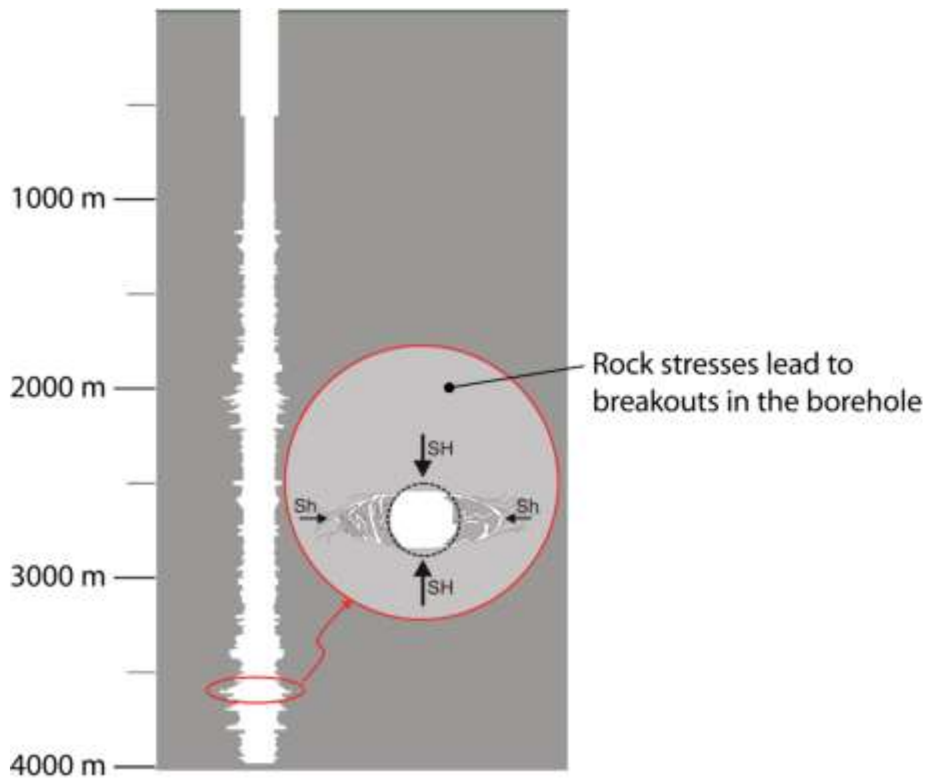

Fig. 6. Illustration of borehole deformations and breakouts due to anisotropic rock stresses. Note that the borehole is not to scale.

CONCLUSIONS

It has been shown that the primary safety function of a DBD repository is radionuclide containment in the deep near-field rock due to the assumed stagnancy of deep saline groundwater. The stagnancy is to be maintained by a combination of low permeability rock and density stratification of the groundwater due to increasing salinity with depth.

Thermal buoyancy and hydrogen formation from corrosion of canisters and casing tubes are threatening processes that put the containment at jeopardy and necessitate efficient sealing measures. It has also been shown that borehole deformation and breakouts will make the design of efficient borehole sealing measures a challenging task. It has therefore been deemed likely that channels along and around the borehole will be present also after the application of sealing measures, and that such channels will be preferred transport paths for hydrogen and potentially radioactively-contaminated groundwater.

While the consequences of the processes described in this paper have not yet been analysed in detail, SKB has taken the position that SNF deposition in deep boreholes is associated with too many question marks to make it interesting for further studies as an alternative method in the Swedish nuclear waste programme.

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