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The Concept of Highly Radioactive Waste (HLW) Disposal in Very Deep Boreholes in a New Perspective

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Abstract

Two basically different concepts for disposal of highly radioactive waste are the often cited KBS-3 method and a concept termed VDH (Very Deep Boreholes). So far, the deep hole concept has been ranked as number two because the canisters are not assumed to be retrievable and because some of the techniques for installation of the waste are not yet at hand. Reconsideration of the design and function of VDH shows that, in addition to the advantage of no transport of released radionuclides by groundwater flow up to the ground level because of the almost stagnant salt groundwater at depth, the rock at depth is considerably less permeable than for mined repositories at shallow depth. A further advantage is that VDH will be less affected by future glaciations. Less good is that precise adaption of canister and seal positions to the rock structure cannot be made until boring of the deep holes is complete. Furthermore, the deep holes need to be supported by casings and all work deeper than 500 m must be made with mud in them. Retrieval of damaged casings and stuck canisters may be more difficult than in mined repositories.

Keywords: borehole, canister, clay, disposal, radionuclide, waste.

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1 Introduction

1.1 Why deep hole disposal?

Main arguments for disposal in deep boreholes are that the high salt content of deep groundwater implies almost stagnant groundwater conditions, and that the rock stresses are so high, 50-110 MPa, at 2-4 km depth that fractures and joints are closed and make the rock tight [1]. Another favourable property is that the risk of illegal capturing of the waste would be less in a deep borehole repository than in the commonly proposed repositories of KBS-3 type at shallower depth (400 m), [2]. Theft of nuclear material from a sealed geological repository would be a large-scale operation that would not escape discovery in a functioning society. The fact that holes with a diameter of several decimeters have been bored to several thousand meters depth demonstrates that storing of waste in deep boreholes is feasible [3], [4].

An argument against the method is that there will be a risk of canisters getting stuck when inserted at depth. A further negative aspect is the need for many deposition sites. Thus, for a country like Sweden with about 10 nuclear reactors with 1000 MW power and 40 year lifetime, successive disposal of canisters can be made in 20-25 years. Four to eight multiple borehole sites would be suitable [4]. We consider this to be feasible because of the comprehensive knowledge about Swedish bedrock conditions respecting groundwater resources and location of exploitable ore. An important condition for avoiding thermal overlap from adjacent holes is that the spacing should be at least 200 m [4].

An issue of importance is that international rules concerning control and book-keeping of fissile material, nuclear safeguards, and use of an adequate system for such control, should be operational until the fissile material is practically irrecoverable. This would require, according to IAEA, monitoring of repositories for spent fuel against unauthorized movement of the disposed material after closure of repositories of KBS-3 type because of the rather easy access via the ramp and shafts. For VDH, monitoring would naturally not be required because of the deep location of the waste and the relatively small amount of waste per hole.

1.2 General conditions for location of VDHs

Two conditions are important for the function of a VDH, the groundwater mobility and capacity of transporting radionuclides, and the movements in the rock with special respect to the risk of canister breakage. Regional hydraulic gradients primarily drive water through major permeable discontinuities appearing as in Figure 1. The same zones also represent active or potential shear or slip planes.

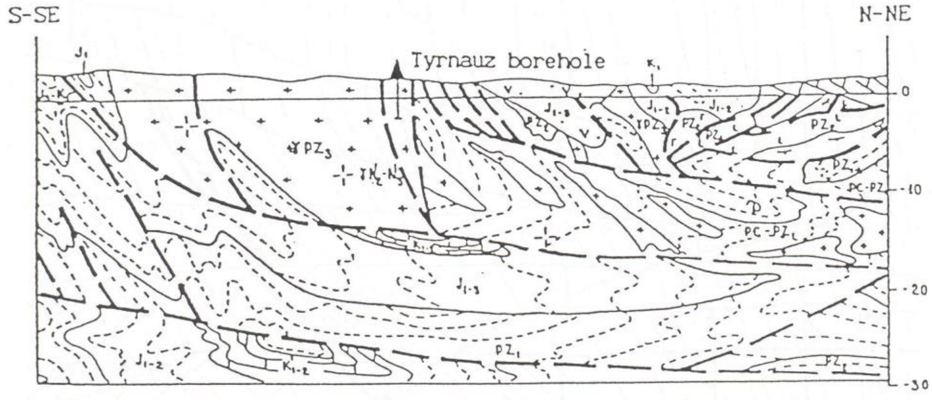

Figure 1: Example of regional structural model from Caucasus. The dashed lines represent weaknesses assumed to be particularly permeable and to serve as slip planes. The horizontal scale is ten times larger than the vertical that extends down to 3.0 km [5].

1.2.1 Geological and hydrological conditions

For visualizing typical crystalline rock structure and getting a basis for estimation of its hydrological and mechanical functions we will use a categorization scheme according to which 1st order fracture zones have a persistence of more than E4 m and a high average conductivity (>E-8 m/s), 2[nd] order zones with a persistence of E3 - E4 m and a medium/high average conductivity (E-9 – E-8 m/s), and 3rd order zones persisting for E2 – E3 m and a medium/low average conductivity (E-9 – E-10 m/s), [6]. We will also refer to discrete water-bearing fractures as 4th order discontinuities with a persistence of E0 – E1 m, taking all other fractures to be of little mechanical and hydraulic importance in the present context.

The number of major fracture zones of 1st and 2[nd] orders intersected by a 4 km deep VDH can be estimated between 2 and 3. The spacing of 3[rd] order facture zones down to 1 km depth is usually 30-100 m implying that VDHs will intersect about 10-30 zones of this type per kilometer. They should all be taken as active or potential slip zones that should not intersect parts of the holes that contain canisters. There may be reasons for assuming larger spacing of major fracture zones at larger depths than 1 km but there is no proof of this.

1.2.2 Stress/strain conditions

The impact of shear strain on the rock structure generated by seismically or tectonically events has been illustrated by simple analytical analyses in 2D, assuming the rock structure model to have large discontinuities of 2nd order and integrated regular systems of 3rd and 4th orders in fractal-like patterns, and taking the primary stress field to be exposed to the principal stresses of 30 and 10 MPa. The friction angle of the 2nd order weaknesses to be 10°, and 15° of the 3rd order fracture zones, while that of discrete 4th order fractures was taken as 25°, all being based on comprehensive literature inventories [6]. The impact of a major seismic or tectonic impact was simulated by rotating the stress field by 45°, causing shearing on the millimetre scale of the discrete fractures of 4th order, by decimetres of the 3rd order fracture zones, and by about one meter of the 2nd order zones (Figure 2). 1st order discontinuities, i.e. very large weak zones, would deform by tens to a hundred meters. Stress field changes of this magnitude do not take place instantaneously but occur stepwise, triggered by large seismic events or intercontinental relative displacements. In the present context we can confine ourselves to take shearing only of 3rd and 4th order discontinuities into consideration. We do this by designing the VDH so that no canisters are placed where it is intersected by water-bearing fracture-rich zones.

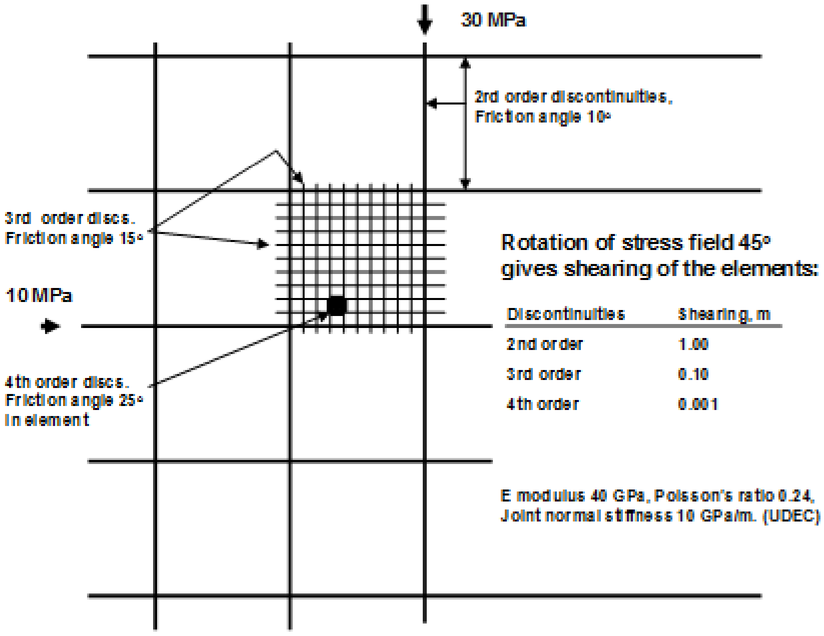

Figure 2: Assumed rock structure model for calculating shear strain of the respective elements. The spacing and persistence of the 3rd order discontinuities is 100 m while the 4th order discontinuities have a spacing of 5 m and a persistence of 25 m (After Hökmark).

1.2.3 Temperature conditions

In Swedish bedrock the temperature rise with depth does not exceed about 1.6°C per 100 m depth, meaning that the temperature at the bottom of the 4 km deep holes is expected to be about 64°C [4]. Two possible canister configurations were considered, one with 4 BWR (boiling water reactor) elements, and one with 2 BWR and 1 PWR (pressure water reactor). The heat production of either of them would give a net temperature at the bottom of the hole of 150°C assuming generally accepted data of the heat generation and thermal properties of the clay and the rock [4].

1.2.4 Salinity

An early proclaimed advantage of VDH is that the concentration of total dissolved salt (TDS) content 100000 ppm at 2-4 km depth [1,5] and the density are so high that convective flow generated by the heat production will not bring possibly contaminated water higher up than about 70 m above the waste-containing part [4]. The Ca/Na ratio deeper than 2 km is expected to be at least 2, while it is estimated to be 1.5 higher up.

2 Early VDH attempt

2.1 Principle and design

The idea of disposing highly radioactive waste in deep boreholes is old and apparently simple: bring the canisters down to a depth of a few kilometers where the rock between fracture zones is very tight and the groundwater stagnant, and then forget about it since only diffusive transport can cause migration of possibly released radionuclides from the canisters. A first Swedish attempt to define a concept for disposal of spent reactor fuel in very deep holes was a study called Project on Studies of Alternative Repository Concepts, Pass, performed by the Swedish Nuclear Fuel and Waste Management Co (SKB) in the end of the eighties and the beginning of the nineties [2,4]. This concept, which is internationally referred to as the most elaborated deep borehole concept so far, was based on disposal of encapsulated fuel in boreholes at a depth between 2 and 4 kilometers. The part extending from the ground surface to 2 km depth was termed “Plug zone” and the one from 2 to 4 km “Deployment zone”.

Figure 3 illustrates the design principle of this concept. Several steep holes would be bored in different directions from a chamber at a depth of some tens of meters below the ground surface. The distance between the waste-bearing parts was taken sufficiently large for avoiding interference and superimposed temperature fields, but sufficiently small to establish a confined common space for rational establishment of the boring site. The earliest concept, representing a “Basic case”, had a hole diameter of 1.675 m from the upper end to 2000 m depth, and a diameter of 0.8 m down to 4000 m, Another option implied 0.76 m diameter down to 3000 m and 0.375 m down to 5500 m depth. While it may well be possible to make stable large-diameter boreholes without support, the concept specified use of casings over the whole borehole length. They were proposed to consist of grids of titanium while todays’ choice would be Navy Bronze – an alloy of more than 90 % copper and 10 % nickel.

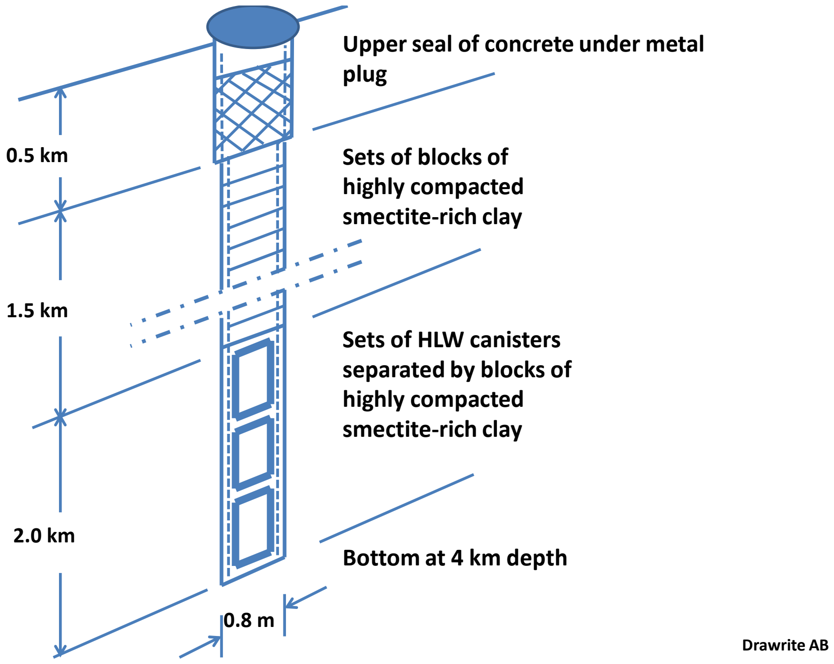

Figure 3: Schematic view of a VDH with constant diameter below the uppermost seal of concrete, originally asphalt, extending down to 0.5 km depth, below which the hole is tightly sealed with clay to 2 km depth. The “disposal” zone with sets of connected HLW canisters separated by clay blocks is shown here in a hole with 0.8 m diameter.

The canisters proposed for the Basic Case with 800 mm diameter deposition holes, which will remain in focus in this paper, were made of titanium. They had an outer diameter of 500 mm, a height of 4760 mm, and a total weight of 3060 kg, of which the thin titanium tube made up 210 kg, the four BWR elements 1210 kg, and a concrete filling 1600 kg. The canisters would be firmly connected to form sets separated by 1 m long cylindrical blocks of highly compacted smectite-rich clay of MX-80 type having a dry density of 2100 kg/m^3. The canister sets, each weighing 12-15 tons, would be pressed down through drilling mud and further down into “deployment mud” proposed to be a clay mixture of 30 % smectite-rich clay and 70 % quartz filler with addition of 10 % NaCl solution, giving a density of 1600 kg/m^3.

This mud would be consolidated by the expanding, dense clay to reach a density of 1900 kg/m^3, which would also be the ultimate density of the expanded core of the initially dense clay block. The hydraulic conductivity of the consolidated mud would be E-10 m/s in 10 % $CaCl_2$ solution, which was conservatively selected for simulating the very salt Ca-rich groundwater at 2-4 km depth. The hydraulic conductivity of the expanded smectite-rich clay block would be E-11 to E-10 m/s for salt water. The mud surrounding the canister sets would retain its density 1600 kg/m^3 and conductivity, which was estimated at E-9 to E-8 m/s.

2.2 Problems in construction of a VDH

2.2.1 Adaption of positions of canisters to rock structural features

The VDH disposal concept was launched without complete understanding of the short-circuiting effect that the deep holes will have on large-scale groundwater flow, which primarily takes place via low-order discontinuities, i.e. those of 1^{st} to 3^{rd} orders. The first mentioned can be found by combination of geophysical methods and deep exploratory borings while small fracture zones below a few hundred meters depth will escape identification. This means that the VDH will intersect an initially unknown number of such zones but some will be found in the early phase of detailed planning the repository by boring pilot holes in the suggested positions of the forthcoming VDHs. The trouble is that steeply oriented fracture zones may intersect the holes over such a large part that the degree of utilization for canister placement may be unacceptably low. The matter requires definition of the criteria for acceptance/non-acceptance of canister positions with respect to rock structural features, or selection of a canister design that eliminates the risk of release of radionuclides caused by rock movements. This latter possibility will be considered in this paper.

2.2.2 Boring disturbance

A major problem, realized early in the evolution of the VDH concept, was the risk of rock fall and unstable rock conditions. Figure 4 shows the results from measurement in the 12 km hole bored at Murmansk, illustrating that the average diameter of the hole varied from the intended 214 mm to 350 mm in the interval 0 to 4000 m, the largest measure being in the interval 1000 to 2000 m [7]. Similar conditions were found for the about 7 km deep Siljan hole in Sweden [4].

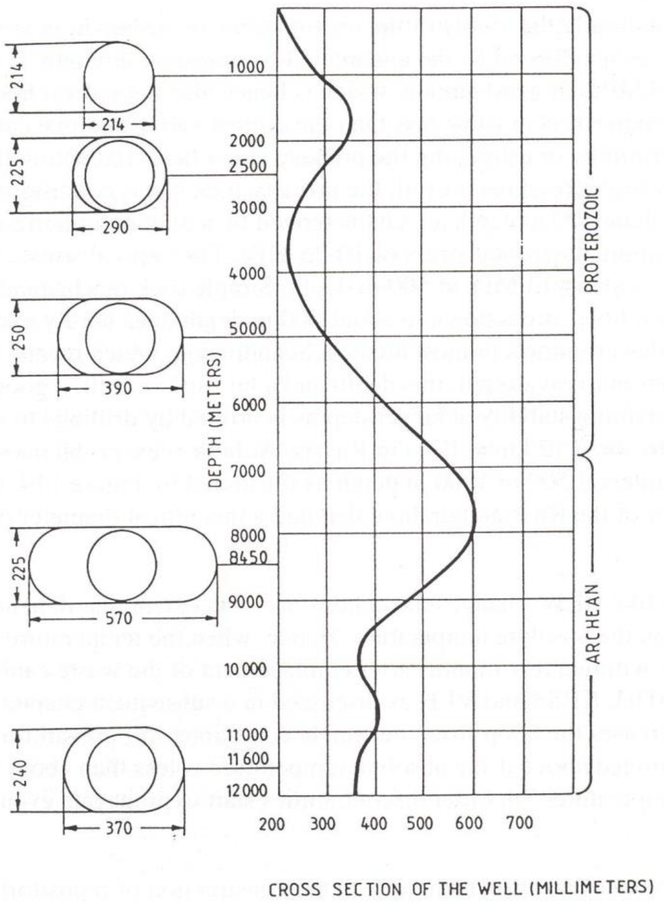

Figure 4: Measured variation in diameter of the 12 km deep Murmansk borehole [7].

The success of boring deep holes and to place waste canisters and seals in them depends very much on the possibility to support the rock by use of casings and muds as evidenced by the very comprehensive experience in the oil- and gas industry. The general understanding is that holes with 0.8 m diameter can be bored to 4 km depth without great difficulties [3] but that local anisotropic increase in diameter by up to 50 % must be expected depending on the rock structure and ratio of horizontal principal stresses. The impact on the rock is caused both by stress changes that can cause rock fall and strong rise of the transport capacity of steeply oriented fractures, and also by fine-fissuring to a distance of a few tens of millimeters from the periphery of the hole (Figure 5). The frequency of wedge fallings, which would leave a larger space to be filled by the clay seals, is believed to be very low because of the stabilizing impact of casing and mud. The 20 mm zone of boring-disturbance has a hydraulic conductivity that is at least 100 times higher than that of virgin rock, which is commonly E-12 to E-10 m/s [6,8].

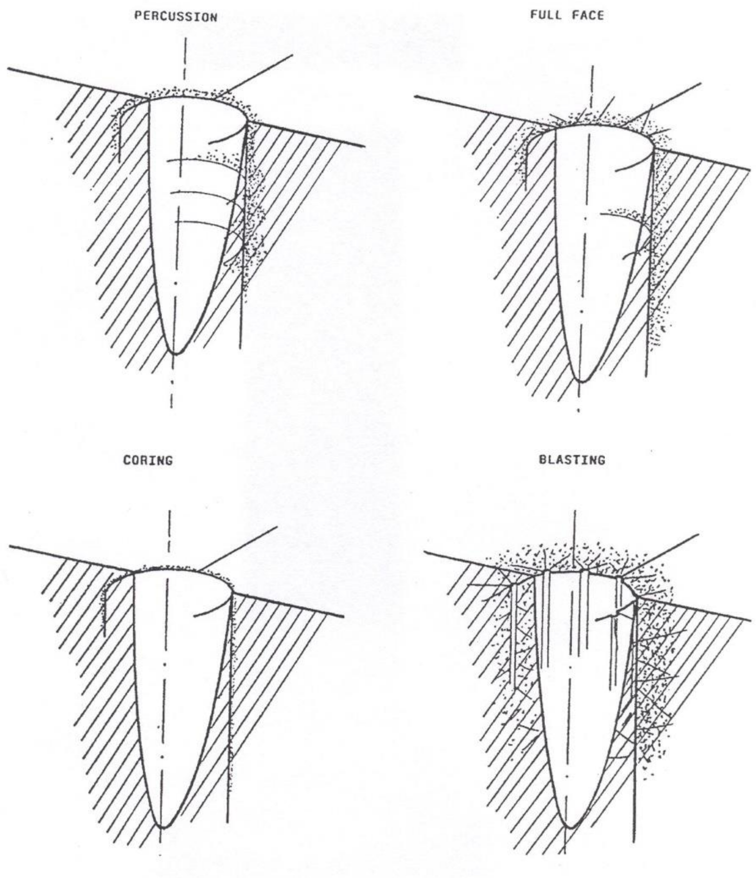

Figure 5: Impact on the stability of boreholes by excavation disturbance and formation of unstable wedges. Upper left: Percussion drilling, causing significant fine-fissuring and fractures normal to the hole axis. Upper right: Full-face boring, causing second smallest disturbance. Lower left: Coring, causing minimum disturbance. Lower right: Blasting, causing maximum disturbance.

The earliest plan was to use water as drilling mud to 3000 m depth and clay-based mud deeper down but this was later changed to keeping the holes filled with drilling mud throughout the construction phase. The mud would have to be thixotropic and easy-flowing at pumping but enough stiff to carry rock fragments on its way upwards to the cleaning plant on the ground surface. It would suitably be based on smectite clay. The casing, which was proposed to be installed from shallow depth down to 4 km depth, would consist of a coarse grid for preventing rock fragments and wedges of the sort indicated in Figure 5, to fall into the holes in the construction and waste application phases.

2.3 Performance of the seals

2.3.1 Risks

The VDH disposal concept has technical problems that were realized early but not altogether solved. They are:

1. The deployment mud surrounding the canisters must remain coherent, meaning that no gaps must be formed between canister sets and seals at the expected temperature 150^{o}C and 100000 ppm TDS,
2. The seals in the holes down to 2 km depth must remain coherent and tighter than the surrounding rock at the expected temperature 20-70^{o}C,
3. Seismically and tectonically generated shearing of the holes must not break the canisters or cause the clay seals in any part of the 4 km deep holes to lose their density and tightness.

Fulfillment of the first criterion requires that the clay components remain expandable and exert a pressure on the confining rock and canisters. The drilling muds must retain their property of gelling when at rest and of transferring rock cuttings from the bottom of the hole to the surface. For this purpose smectite-rich clay (“bentonite”) as primary viscosifier works well as long as the temperature is less than about 100^{o}C. At higher temperature it can lose these properties and at a constant temperature of 200^{o}C over longer periods of time it can be transformed to shale.

Herbert et al [9] made laboratory investigations of the commercial, smectite-rich MX-80 (smectite-rich clay with montmorillonite as major clay mineral), involving isotropic hydrothermal treatment of the clay saturated with NaCl- and a $MgCl_2$-rich brine at 25, 90 and 150^{o}C, at pH=1, 6.5, and 13 for nearly two years. Although montmorillonite was found to remain as dominant clay mineral at all temperatures and all pH levels, significant changes were found respecting crystallinity, particle thickness, interlayer charge, and chemistry of the octahedral layers. The tests showed an obvious trend of montmorillonite to be converted to kaolinite and pyrophyllites rather than to illite. A most important effect was the loss in hydration potential, and hence in expandability. A 3-year study by Kasbohm of equally dense samples of the same clay type using seven characteristic saline solutions, including also pure water verified this [10]. The swelling pressure, i.e. the common measure of expandability, was highest for the latter (>4 MPa) and significantly lower for the solutions with low ionic strength (2 MPa) and lowest for the brines (< 1 MPa). Partial dissolution of montmorillonite was observed giving increasing amounts of Mg, Al and Si with reaction time. In the octahedral layers of montmorillonite, Mg was substituted by Al causing first a decrease in interlayer charge, and later, loss of some octahedral layers by which excess Si in the montmorillonite particles. This may all have been caused by processes leading to pyrophyllitization/kaolinitization and Si-excess of the montmorillonite particles, while illitization was less likely.

A number of studies by Herbert et al [11], Kolaříková et al [12] and Xiaodong et al [13] have indicated that montmorillonite-rich clays loose a significant part of their swelling potential when exposed to a temperature of 90°C under relatively high thermal gradients (15°C per cm), and even under isothermal conditions, especially at high porewater salinities. The primary reasons appear to be precipitation of cementing silicious compounds and conversion of montmorillonite to non-expandable clay minerals. The rate of the process, which is complexed by transient gradients and ion concentrations, is believed to be of Arrhenius' type but the controlling activation energy for the dissolution/precipitation is not known.

The consequence of significant reduction of the expandability is that the continuity of the system of components in the deployment zone, i.e. the canisters, deployment mud, clay blocks, and rock may be lost and gaps formed. They will serve as flow paths for contaminated water and can bring radionuclides up to the plugged zone and further up to the ground surface via the boring-disturbed EDZ (cf. Figure 5, "full-face"). This zone, estimated to be at least 20 mm deep, has a transport capacity of 50 ml per year for a hydraulic gradient of 1 m/m, while the capacity of a corresponding annulus of undisturbed rock would be less than 0.5 ml per year [6, 8].

Fulfillment of the second criterion requires that the expandability of the smectite clay is preserved for hundreds of thousands of years at up 70^{o}C and 50000 ppm TDS. This is expected to be the case, at least for the upper 500 m where the temperature will not be higher than 20^{o}C and the TDS less than 500 ppm. It is required, however, that the density is preserved, which can be jeopardized by expansion of the clay out into fracture zones where groundwater flow can cause erosion and loss of the migrated clay.

Fulfilling of the third criterion requires that the canister can sustain rock shear strain without failing. The proposed thin-walled titanium canister filled with concrete would fail already in conjunction with the installation by tension stresses at the junction of its stiff end plates and the cylindrical part, which will be strongly compressed by the very high water pressure, i.e. 20-40 MPa. This would cause immediate release and transport of radionuclides to the ground surface.

2.3.2 Intersection of zones

The role of fracture zones that will be intersected by a VDH with a frequency of 30 to 100 per kilometer depth has not been fully realized by earlier VDH investigators. It is particularly important for successful construction of the holes and also for the function in a long-term perspective because of the risk of loss of clay into them. It is also required that their role at seismically generated rock displacement is taken into consideration since shearing primarily takes place along such zones. These zones are hence major threats to VDH performance.

3 New VDH concepts

3.1 Design principles

A principle of borehole sealing that has been used in practice on a large scale implies effective sealing of the parts of the boreholes where the rock is tight, and filling the parts that intersect water-bearing fracture zones with physically stable, low-permeable material was proposed by Pusch & Ramqvist early this century [14]. The tight seals consist of smectite-rich clay in the form of highly compacted blocks, while the fillings separating them are made of concrete cast on site (Figure 6). This method is proposed to be used also for VDH.

The major features of the proposed VDH are the same as for the one described in Section 2.1 and illustrated by Figure 3. The difference is that the drilling mud will also serve as “deployment mud” into which sets of jointed super containers with tightly fitting canisters are inserted in the deployment zone, while in the plugged zone down to 2 km depth; they contain tightly fitting blocks of buffer clay. The deployment zone host super containers with canisters and clay blocks. They shall be made of metal that is chemically compatible with the canisters and copper is a primary candidate. For strength reasons the super containers and also the casing are preferably made of Navy Bronze with 90 % copper and perforated with circular or quadratic openings corresponding to 50 % of the total surface area. All container sets rest on previously inserted sets except where fracture zones are intersected. Here, concrete is cast up to the level where the fracture zone ends. The next sets of canister-containers are inserted when the concrete has matured to get the required bearing capacity. Schematically, a VDH unit would look as in Figure 7. Depending on the amount of radioactive waste and length of the canisters, clay blocks may have to be incorporated as distance blocks between each or every second or third canister for avoiding criticality.

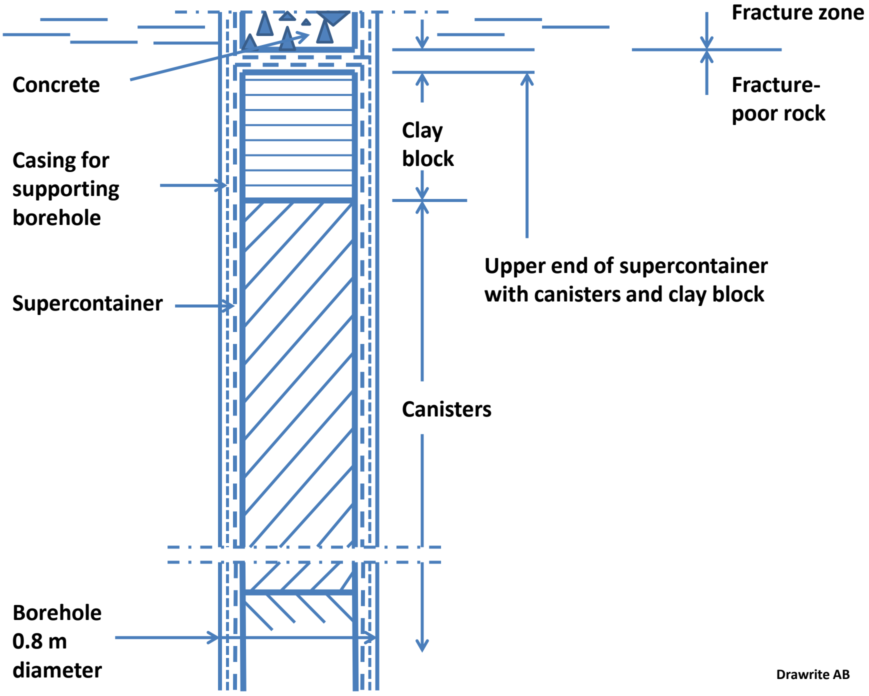

Figure 6: Principle of composing super canisters in the deployment zone.

Above 2 km depth, i.e. in the plugged zone, the same arrangement is proposed but with compacted clay blocks in all super containers. Where fracture zones are intersected reaming and stabilization is made in the way indicated in Figure 7, requiring that the casing is interrupted and replaced by a rock-supporting concrete plug that is keyed in the rock.

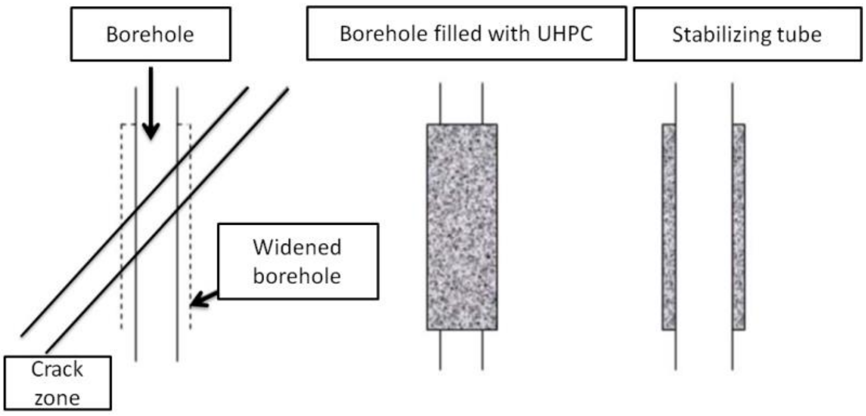

Figure 7: Technique for stabilizing boreholes. Left: Borehole intersecting fracture zone, Center: Reamed hole filled with concrete between packers, Right: Re-boring giving a stabilized hole [15].

3.2 Construction and performance of the VDH

3.2.1 Preparative work

Pilot corings will give all necessary data respecting the geometry of the hole (leaning and diameter variation) and of the rock constitution respecting petrology, groundwater composition, piezometric conditions, and distribution of fractures, which is the basis for working out a scheme for location of canisters and seals. This scheme will show where special measures have to be taken in the full-size holes to be bored, like stabilization by grouting or reaming and casting of concrete followed by re-boring. Detailed planning of these activities has to be made well in advance of the full-face boring.

3.2.2 Clays

3.2.2.1 The mud

The proposed principle is to use a bore mud that can also serve as deployment mud. Its main purpose is to support the rock and bring up the rock fragments in the boring phase and continue to support the rock thereafter. The stiffening of smectite-based mud in the entire hole will initially only be due to the microstructural reorganization that is associated with the thixotropic strength regain since no significant chemical changes will take place under the moderate temperature conditions that prevail until the super containers with canisters are installed ($<70^oC$). The sets of canisters in super containers are assumed to be cooled to the freezing point before they are brought down and held in transport tubes until they are lowered into the holes where they sink in the soft mud down to the planned depth. The viscosity of the mud, which can have a density of about 1600 kg/m^3, drops initially but stiffening by dissolution/precipitation mechanisms is expected when the temperature rises to the predicted temperature of around 150^oC. The uppermost part of the super container with canisters contains clay blocks that expands and start consolidating the mud around it, hence creating a tight seal. The next canister sets are installed up to a few meters below the first fracture zone and concrete pumped in through a tube to a few meters above its upper boundary, by which the mud is displaced and pressed upwards. Since the clay seal formed at the upper end of the latest placed super container with canisters becomes stiff in a few days the cast concrete will not penetrate downwards along the super container.

3.2.2.2 The clay blocks

A most important issue, neglected by earlier concept developers, is that the clay blocks in the super containers start expanding already immediately after placement, which increases the resistance to bring them down. It is therefore essential to retard the hydration in the installation phase, which can be made by coating the blocks with a mixture of smectite clay and talc [16].

The hydration of the clay blocks in the super containers starts when the coating of them has been penetrated, which is a matter of one day. At low water pressure the water uptake, being of diffusive type, is very slow and a cubical block of 1 m^3 would require thousands of years to become fully water saturated (cf. Figure 8). However, under the very high water pressure that prevails in the deployment zone water enters the very dense, initially unsaturated clay by combined channel-wise inflow and diffusive wetting, causing much quicker saturation [10].

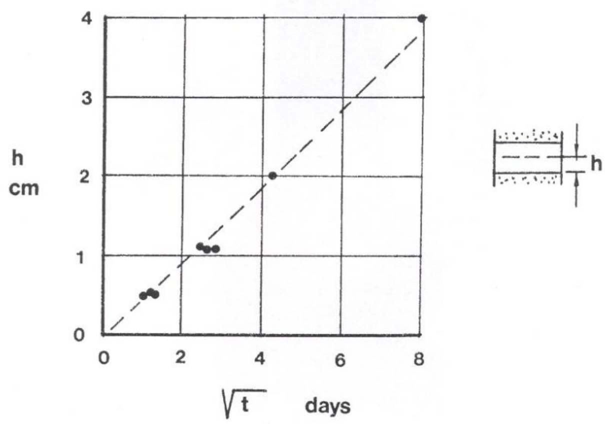

Figure 8: Example of the rate of water saturation by suction of block of compacted smectite-rich clay with a dry density of 1450 kg/m3. Complete saturation leading to a density of 1900 kg/m^3 by 2-sided uptake of water takes 4 days for a 1 cm thick sample and two months for a 4 cm sample. An 8 cm sample would require almost 1 year.

3.2.2.3 Selection and performance of clay for sealing the VDH

The search for sustainable expansive clays in hot environment has been in focus of the oil- and gas industries' interest for more than a century, primarily for finding drilling muds that retain their thixotropic properties in the course of drilling deep holes. While these companies have no restrictions respecting addition of organic substances for making the mud fluid and thixotropic such components are not allowed for use in VDHs, neither in the boring phase nor for preparing clay seals because of the risk of formation of organic colloids that can carry radionuclides [2]. Only inorganic minerals can be accepted like smectites and mixtures of this clay mineral and rock-forming minerals like quartz.

The role of the clay blocks at the upper end of the sets of super containers with canisters is to provide support to these sets for keeping them centered in the VDH and for providing a sufficiently stiff base for casting concrete where it intersects fracture zones. They shall also prevent significant axial heat-induced flow of water and mud in the deployment zone. The whole idea is that the major waste-isolating function shall be provided by the expanded clay blocks in the plugged zone while the components in the deployment zone only have to secure axial continuity and confinement of the waste.

3.2.2.4 The zones

Deployment zone

Requirements for the mud: a) thixotropy in the boring and waste installation phases, b) sufficiently low viscosity at installation of super containers, c) sufficient stiffening and bearing capacity for preventing cast concrete to displace mud below.

Requirements for the clay blocks in the canister super containers: sufficient expandability to maintain interconnectivity of the components mud, super containers, clay blocks and concrete seals.

Plugged zone

Requirements for the mud: a) Thixotropy in the boring and seal installation phases,

b) Sufficiently low viscosity at installation of super containers,

c) Sufficient bearing capacity for preventing cast concrete to displace mud below.

Requirements for the clay blocks in super containers: a) sufficient expandability to maintain interconnectivity of mud, super containers, and concrete and clay seals, b) lower hydraulic conductivity than the surrounding rock of the matured clay. Examples of smectite clay candidates are listed in Table 1, the difference being the crystal structure. Saponite has Mg in the octahedral layers, while montmorillonite has Al [6].

Table 1: Major properties of clay candidates, saturated with 3.5 % CaCl2 [6].

Dominant clay mineral	Density, kg/m^3	Hydraulic conductivity*, m/s	Swelling pressure, MPa	Potential to undergo loss in density by migration into fractures
Montmorillonite	2000	2E-13	4.7	Very substantial
Montmorillonite	1900	5E-12	3.0	Very high
Montmorillonite	1800	5E-11	1.0	High
Saponite	2000	5E-13	8.8	Medium high
Saponite	1800	E-12	2.5	Low

*Determined by oedometer tests with hydraulic gradients lower than 50

The hydraulic conductivity and swelling pressure are practically the same as in Table 1 for higher salt contents but the conductivity significantly lower for low salinities. The swelling pressure is significantly higher for low salinities [6].

3.2.2.5 Assessment and candidature of clay constituents

Rheology

The most important requirements of the mud are that it must be thixotropic and sufficiently soft for allowing the super containers to sink. Assuming their weight to be 20 tons they will exert a pressure on the mud of about 1 MPa and generate shear stresses of around 200 kPa[1], hence requiring a shear resistance lower than that. For mud of Na-montmorillonite saturated with low-electrolyte tap water the shear strength is on this order for a density of 1600 kg/m3 but uptake of Ca chloride to a salt content of 3-10 % which will happen in the deployment zone, the shear strength will drop to less than 50 kPa hence making the mud soft and 10 to 50 times more permeable [6]. Lower density than 1600 kg/m^3 would make it heterogeneous by strong coagulation. The shear stresses by own weight can be increased by using vibratory heavy pile-driving equipment if required.

In the deployment zone the mud will remain soft after placement of the super containers except where it eventually becomes consolidated by the expanded clay block in them. The ultimate density of the mud/block here as well as in the plugged zone, will be about 1900 kg/m3 at equilibrium, assuming that the initial (dry) density of the block is 2050 kg/m3,

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[1] Basic soil mechanics defines the ratio of bearing capacity and (undrained) shear strength
[2] This technique has been successfully used for releasing large-diameter wells stuck in clay (Ref.

which is reached by compressing very dry smectite granules under 100-200 MPa pressure [14]. The ultimate hydraulic conductivity, which will be about 5E-12 m/s according to Table 1 for montmorillonite and saponite, is lower than the conductivity of the surrounding rock represented by the 20 mm boring-induced EDZ [6,8]. The density is also high enough to make it impossible for microbes to multiply and migrate in the clay [6]. Where the holes have been significantly widened in the boring phase, implying lower ultimate density of the clay, concrete plugs should be cast.

Erodability

A recently identified possible degradation process is that smectite clay can migrate out from blocks with high density into open fractures in the surrounding rock where it can be eroded and carried out into the rock by flowing groundwater. While the salinity of the groundwater will not cause spontaneous dispersion of clay in the deployment zone and the larger part of the plugged zone, the clay in the upper 500 m of the plugged zone may undergo slight depletion after a major glaciation cycle when electrolyte-poor melt water can percolate the repository rock and maximize the expandability and dispersivity of the clay. The risk is highest for the most expandable candidate, i.e. montmorillonite, and lower for saponite.

Impact of heat

In a short term perspective the practically most important impact of heating of yet unaltered clay is on the hydraulic conductivity of the unconsolidated mud in the deployment mud and of the clay formed by expansion of the clay blocks and consolidation of the mud in the deployment and plugged zones. The primary effects are reduction of the viscosity of the pore water and coagulation of the unconsolidated mud [6]. In a longer perspective the chemical stability of smectites will determine the hydraulic conductivity and expandability as indicated in Section 2.3.1. The outcome of the 8 week hydrothermal experiments performed by Xiaodong et al, [12], with 90°C temperature at the heated end of 50 mm long specimens saturated with 3.5 % $CaCal_2$ solution, was that MX-80 clay had undergone very significant loss of expandability and a hundred-fold increase in hydraulic conductivity, while saponite clay retained its expandability and had its conductivity less changed. Herbert et al. [16] assumed that Na-rich and Fe-poor bentonites from acidic or intermediate parent rocks with high thermal impact as geological background of bentonite formation (>> 70°C) can better resist any heat impact on technical barriers (e.g. Wyoming bentonite from deposits with hot ash fall into sea or hydrothermal smectite like Kunipia F [17]). Also saponite is obviously preferable [6, 17]. The occupation of all three octahedral sites in trioctahedral smectites seems to be the key for the stability of this smectite species [18].

Using Table 1 as a basis of ranking the clays and considering also the chemical stability, which determines the risk of stiffening by precipitation of dissolved mineral particles, the most suitable clay material is saponite as concluded from the arguments presented, primarily the outcome of THMC experiments [12,17] and the experience from using saponite drilling muds in deep boreholes [19].

3.2.3 Concrete

The proposed principle of constructing concrete seals where the VDH intersects fracture zones requires consideration of their physical performance and the chemical impact they have on adjacent clay seals. A most important fact is that ordinary concrete with Portland cement as binder is not acceptable, firstly because of its poor chemical stability and secondly by the rise of pH of the pore water to more than 12, which has a strong degrading effect on contacting clay seals. There is also a third, major argument: organic super plasticizers which are indispensable for making concrete fluid, must not be used since they can give off organic colloids that can transport radionuclides. Inorganic fluidizers like talc and use of low-pH cement offer new possibilities to prepare suitable concretes for use in boreholes [20]. The criteria for the concrete seals are:

- Sufficient fluidity for casting, which is made by use of containers [6],
- Sufficient bearing capacity to carry the next super container to be installed, without concrete being pressed up along it,
- Sufficient bearing capacity to carry the whole overlying series of super containers, taking the wall friction (“silo effect”) and adherence to the walls of the expanded clay blocks into consideration,
- Lower hydraulic conductivity than of the fracture zone,
- Sufficiently high bearing capacity and low hydraulic conductivity in the requested period of time, this is taken as 100,000 years by organizations like the Swedish Nuclear Fuel and Waste Handling Co (SKB), even if the cement component is dissolved and lost [2].

For fulfilling the requirements the concrete must have a high density, at least 2100 kg/m^3, and a very low content of cement. The cement must be fine-grained and of low-pH type and represent about 5-8 weight percent of the solids. The aggregate should consist of silica-rich grains of low roundness. An example of the recipe of the patented concrete is shown in Table 2.

Table 2: Theoretical and optimum packing of concrete (low-pH cement) [20].

Concrete ingredients	Packing degree ($\tan \varphi$)		Mix proportions (%)
	Actual	Theoretical	
		Average	
Cement	0.495	0.497	5
Talc			9
Crushed quartzite			60.2
Ground, crushed quartzite			25.8

The concrete, which will be pressed out under the deployment mud, is suitably compacted by a heavy vibrating tool like those used for deep pile-driving, attached to the concrete container. The concrete gets sufficient bearing capacity and a hydraulic conductivity of less than about E-11 m/s in one week. The ultimate bearing capacity and hydraulic conductivity after dissolution and loss of the cement component are believed to be of the same orders of magnitude as for dense moraine. Basic parts of the concept have been successfully applied in practice, providing sealing of a borehole of limited length (500 m) but full-scale testing is desired and required for licensing [6,13].

3.2.4 Canisters

The titanium canister with concrete embedding spent fuel that was proposed by earlier investigators is judged to be too brittle to sustain compression under 40 MPa water pressure and would give off radionuclides even before closing the VDH. Copper is a preferable canister material but the hollow copper/iron canister types proposed by SKB would also yield. The ideal design is represented by the HIPOW canister made by hot isostatic compression of non-oxidized copper powder in copper tubes with the bundles of spent reactor fuel submerged in the powder [6, 21]. The technique needs some further development but is considered feasible. Alternatives that are presently worked on involve placement of four BWR elements in copper tubes followed by filling them with copper powder and sealing them by friction or electron welding of semi-spherical end pieces of copper.

4 Discussion and recommendations

The organizations responsible for working out concepts for final disposal of highly radioactive waste in crystalline rock have proposed mine-type repositories with blasted tunnels and shafts at some 400 m depth and bored holes for placing HLW canisters. Some have proudly stated that the designs are based on the multi-barrier principle, implying that the canisters, their embedment in clay, and the host rock combine to prevent radionuclides to migrate to the biosphere. In recent years the barrier role of the repository rock has been questioned leading the present authors to ascribe the role of such rock to be a mechanical protection of the “chemical apparatus”, i.e. the waste, rather than to be a barrier to migration of radionuclides [22]. The poor waste isolating capacity of shallow crystalline rock led them to consider solutions according to which the nature and role of the repository rock is subordinate, of which the VDH concept is an example. It necessitates, however, development of techniques for preparing very long-lived canisters.

The principle of VDH has the following advantages as described in the paper:

- The thermal output from the spent fuel is insufficient to alter the stable location at depth of the near-stagnant groundwater,
- The rock at more than 500-1000 m depth is low-permeable except for the fracture zones, in which no canisters will be placed. The concentration of rock slip to these zones minimizes the risk of randomly distributed shearing,
- In contrast to earlier investigators we believe that the type of smectitic mud used in the boring phase can also be used in the waste and seal application phases,
- The amount of excavated rock will be much smaller than for mined repositories,
- The construction time will be much shorter than for mined repositories and the cost - excepting the expenses for developing a suitable canister production method - probably lower,
- The impact of glaciations will not reach deeper than to 500-1000 meters [2],
- The VDH concept would be particularly suitable for countries with limited quantities of highly radioactive waste. If the waste is in the form of spent reactor fuel the whole fuel-utilization-waste cycle would be practical and economical.

Disadvantages that one can foresee are:

- The holes need to be supported by casings and all work deeper than 500 m must be made with mud in them,
- Adaption of the canister and seal positions to the rock structure may require boring of several slim holes that have to be carefully sealed,
- Intersection of a VDH by steeply oriented fracture zones will reduce the degree of utilization considerably but the risk of such conditions can be minimized by very careful characterization of the rock structure in the site selection phase,

- Retrieval of damaged casings and canisters stuck in the holes is claimed to be more difficult than in mined repositories but frequent use of dummies in the waste placement phase and proper dimensioning of rigs for lifting such objects is significantly better than when VDH was first discussed some 20 years ago. Electro-osmotic treatment using the canisters as cathods and the casing as anode will increase the water content at the canister surfaces and reduce the shear resistance at hoisting [3].

Weighting the advantages and disadvantages it is felt that the VDH concept is worth to be seriously considered as an alternative to the presently considered HLW repository concepts implying shallow location and use of mining techniques. The detailed design may involve changes in diameter and selection of materials. Selection of a suitable canister type is challenging but within reach.

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