The geological basis for developing concepts for disposal of highly radioactive waste (HLW) in crystalline rock – a state of art compilation

R. Pusch¹*

Recebido em 30/09/2011 / Aceite em 09/12/2011

Artigo estado da arte
Article state of the art

Abstract: Concepts for deep geological disposal of highly radioactive waste from nuclear reactors consider the host rock to be a major barrier to transport of radionuclides that may possibly be released from the repository to the biosphere. This has required development of hydraulic (“geohydrological”) models for predicting possible groundwater contamination and dose rates. They are based on very limited information on the constitution and properties of the large rock mass, making the sophisticated models hypothetic and uncertain in calculation of groundwater flow and transport of dissolved species. Considerable effort has been put in hydraulic modeling of groundwater movement during and after the next glaciation cycle, largely disregarding from possible long-term impact of tectonic movements and seismic events on the transport paths. The rheological performance of the “near-field” rock has been assessed without considering that the rock stresses will cause spalling and fracturing of the rock immediately surrounding the waste containers, which produce heat and generate thermally induced stresses. Modelers of the hydro/mechanical performance of the near-field rock mass tend to neglect the existence of excavation disturbance of the rock around tunnels and drifts, which means that the evolution of groundwater flow in the “near-field” and “far-field” in a time perspective that includes at least one glaciation event has not yet been adequately predicted. In conclusion, one must rely on the engineered barriers, waste containers and embedding clay, for safe disposal of highly radioactive waste and take the rock to serve merely as a mechanical protection of the “chemical apparatus”.

Keywords: crystalline rock, hydraulic models, structural models, nuclear waste repositories.

1. Scope

Deep geological disposal of highly radioactive waste is being considered in a number of countries utilizing nuclear power, Sweden and Finland being the first to propose and investigate the function of concepts intended for implementation in crystalline rock Svenmar, 2005. The general principle proposed in the early eighties, implying isolation of spent reactor fuel in metal canisters embedded in dense smectite clay, is still valid but the detailed design has been significantly changed. There are several options, in fact, some of which are described in the paper.

2. Disposal of highly radioactive waste (HLW)

2.1. Disposal rooms

The constitution of the “near-field” depends on the type of rock. In the international work on development of concepts for HLW disposal conducted under the lead of the European Commission and the IAEA, distinction has been made between crystalline rock (including magmatic, igneous and metamorphic types, but excepting carbonates), argillaceous rock (clay shale, claystone), and salt rock (Svenmar, 2005). Only crystalline rock will be considered here since it is presently favoured in several countries.

Different concepts for disposal of highly radioactive waste have been proposed by the national organizations that are responsible for disposal of highly radioactive waste from nuclear reactors. The example in Figure 1 shows essential parts of the planned Swedish repository KBS-3V with a series of 300 m long blasted disposal tunnels with 5 m height and width, spaced about
40 m. The tunnels extend from transport tunnels and are oriented in the direction of the major principal rock stress for minimizing the hoop stress (Svemar, 2005).

In the early eighties a concept was proposed in which every second deposition hole was oriented +45 degrees off the vertical for reducing the temperature-induced rock stresses and this principle was introduced again in recent time in somewhat altered form for the same purpose and for simplifying the canister installation, as described later in the paper. The nature and constitution of the "near-field" depend on the type of rock and on the methods for excavation of holes and tunnels. This matter has been investigated in the international work on development of concepts for HLW disposal conducted under the lead of the European Commission and the IAEA (Svemar, 2005). It showed that blasting of tunnels causes unloading of the rock next to the periphery, while tunnel boring gives negligible disturbance and leads to hoop stresses at the tunnel periphery that can be critically high. Overlapping local stress fields around individual depositions holes can combine to give breakage by fracturing, which can raise the hydraulic conductivity very much depending on the their spacing and orientation, which is different for the commonly proposed concepts shown in Figure 2.

Four conditions determine the possibility to identify suitable sites for HLW repositories, to build them, and to make them serve for the required period of time, i.e. 1) constructability, 2) groundwater flow, 3) rock strength, 4) seismicity and tectonics. The time during which the repository must provide the required isolation potential varies among the countries. While it was earlier taken to be a few thousands to some tens of thousands of years it is presently defined as 100 000 years by many of them (Svemar, 2005; SKB, 2011). In certain countries the host rock of the repository will hence be hit by at least one major glaciation cycle, causing considerable changes in stress, strain, and temperature in the rock.

2.2. Options

The nice properties of crystalline rock is the high strength and stiffness, a less good one being the high and varying hydraulic conductivity. The stability of drifts, tunnels and rooms is generally high but underground construction can be difficult at larger depths where the rock stresses are high (Figure 3) and where tunnels and shafts pass through weak zones that are rich in fractures and clay. As indicated by the comments to Figure 1 the repository wi...
strength parameters of discrete fractures and fracture-rich zones, since they are essential for classifying the rock with respect to stability and for conducting stability analyses (Svemar, 2005). The problem is that core samples from deep boreholes for determination of rock strength represent such a small fraction of the rock mass hosting a repository, usually 1/10000000 (SKB, 2011), that statistical treatment of the data is of very low value. One must therefore take averaged strength data as a basis for predicting how stable tunnels and rooms will be and simplify the rock structure to consist of only major structural features, to which typical physical properties are ascribed, like the strength and the hydraulic conductivity and transmissivity. For the planners of repository construction and for those who are responsible for performance and safety analyses it is necessary to characterize the various rock structural features and this is done by referring to categorization schemes like the one in Table 2.

Table 2. Categorization scheme for rock discontinuities (Svemar, 2005; Pusch, 2008).

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Characteristic properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td>Length, m</td>
</tr>
<tr>
<td>Low-order (conductivity and strength refer to the entire discontinuity as a whole)</td>
<td></td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>E4</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>E3-E4</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>E2-E3</td>
</tr>
<tr>
<td>High-order (conductivity and strength refer to rock with discontinuities of lower order)</td>
<td></td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>E1-E2</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>E0-E1</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt;</td>
<td>E-1 to E</td>
</tr>
<tr>
<td>7&lt;sup&gt;th&lt;/sup&gt;</td>
<td>E-2</td>
</tr>
</tbody>
</table>

E denotes the log scale exponent, i.e. E4=10000, E1=10, E-2=0.01 etc.

A generalized structural model containing low-and high-order discontinuities is shown in Figure 4. One recognizes a major discontinuity (“1”) that can represent San Andreas Fault in California, a few 2<sup>nd</sup> - and 3<sup>rd</sup>-order fracture zones and a system of more or less interacting 4<sup>th</sup> order fractures. In the smallest block with 5 to 50 m edge length, 5<sup>th</sup> order fractures form a subsystem in the network of 4<sup>th</sup> order fractures. This scheme is similar to those proposed in other countries and is helpful in visualizing rock structure to engineering geologists, constructing teams and modellers.

### 3.3. Hydraulic performance

**Far-field and near-field functions**

In practice, the physical behaviour of rock depends almost entirely on its discontinuities. For predicting its thermal, mechanical and hydraulic performances in bulk one needs to use definitions of structural elements with typical properties respecting the hydraulic function and rheological performance. Such calculations must be made for assessing the overall function of the repository in the construction stage as well as in a long-term perspective, i.e. the operative phase. The performance after a few hundred years will be increasingly affected by waste-generated heating and large-scale tectonics in the form of earthquakes, shear displacements, and rotation of regional stress fields.

Minor fractures and fissures of 5<sup>th</sup> and higher orders in the “near-field” play a role for diffusive transport of water and radionuclides but practically important migration takes place in interacting, macroscopic features of 4<sup>th</sup> and higher orders. Those of 4<sup>th</sup> order are hydraulically important and can undergo shearing by stress changes generated by tectonic movement affecting 3<sup>rd</sup> and lower- order discontinuities. Water-bearing major structural elements representing 1<sup>st</sup> and 2<sup>nd</sup> order discontinuities in the “far-field” are of primary importance in the site-selection process and for regional transport modelling and prediction of tectonic movements, while for the “near-field” rock, surrounding deposition holes and tunnels, one would only be concerned with 4<sup>th</sup> order discontinuities (Figure 5). Discontinuities of 3<sup>rd</sup> order, i.e. minor fracture zones, have a
spacing that is sufficiently small to make them intersect a number of rooms in a repository.

Fig.5. Typical 4th and 5th order discontinuities in 0.76 m diameter hole at 360 m depth in SKB’s underground laboratory at Stripa. The fat arrow indicates North direction; the blue and green planes are 4th order water-bearing fractures; and the red planes closed 5th order fractures compressed by a normal stress representing the major horizontal principal stress. The highest hydraulic conductivity is usually in the direction of the major principal stress (SKB, 2011).

The techniques for identifying and characterizing rock discontinuities of 1st and 2nd orders are well known in engineering geology, i.e. deep core drilling and cross-hole geophysical methods in the site selection phase, while discontinuities of 3rd and higher orders can usually not be revealed until the construction phase is entered since most of them do not reach up to the ground surface. The problem of building structural models that include most types of discontinuities has called for use of statistically based or probabilistic “fracture” models like the hydrogeological DFN code (Svemar, 2005; Rhén 2009). They commonly assume the fractures to have the form of thin circular slots that let water through via their crossings. The actual flow paths in fractures are in fact thin channels with a flow capacity that depends on the normal effective pressure. This pressure changes with the temperature, which means that the rock around deposition holes with heat-producing canisters will undergo a successive change in transmissivity in the first 1000 years after canister installation related to the radioactive decay (Svemar, 2005). Tectonics and seismic events will have a corresponding impact on the water-bearing structural elements in all parts of the host rock, which means that calculation and prediction of groundwater flow on any scale is very uncertain. Only fracture zones of 1st, to 3rd order can be considered and taken as water-conducting elements in serious hydraulic modelling of the host rock. This is supported by the finding that piezometric measurements in deep boreholes intended to validate large-scale hydraulic models have not been very successful (SKB, 2011).

The uncertainty in large-scale hydraulic modelling of the “far-field” by use of statistically based hydrogeological models indicates that modelling should preferably be made by defining a simple physical model of interacting major discrete fracture zones of 1st and 2nd orders with field-determined bulk physical properties, taking the rest of the rock mass to perform as a porous medium with an average bulk hydraulic conductivity (Figure 6).

For the “near-field” the same principle is suggested, i.e. that the hydraulic performance is taken to be controlled by discrete discontinuities of 3rd and 4th orders assuming the rock matrix to behave as a porous medium with a certain low average hydraulic conductivity.

Fig.6. Simplified and generalized models of two potential repository sites. The light green areas represent the ground surface and the blue plates 2nd order discontinuities with 100 m width. The red plates are 2nd and 3rd order discontinuities with 50 m width. Black panels with parallel rows of deposition tunnels are integrated at two depths in the upper model, which represents conditions with few major discontinuities. The lower shows a candidate case with more discontinuities and more extensive groundwater flow in the rock mass. No panels are marked (Pusch, 2008).

3.4. Mechanical performance

Large-scale processes affecting repository stability and tightness

A prerequisite for rock displacements that can cause significant changes in the hydraulic performance of large rock units and generate damaging strain is that critically high stresses prevail or be generated. It is recognised that large vertical and subhorizontal movements can occur in the earth crust by slip over faults and potentially lead to destruction of underground constructions and even tsunamis (Pusch, 2008). The issue is of course to identify and avoid such regions in the site selection process.

For assessing the risk that the repository host rock will undergo critically large strain one can make local stress measurements for relating them to data accumulated within the World Stress Map Project (WSMP), (Pusch, 2008). They contain stress orientations obtained by different geophysical methods representing earthquake focal mechanisms. For implementation the theory for transition of discrete data into continuous stress fields requires further investigations in order to provide mechanically consistent models of large rock blocks. Recently, models have been worked out based on stress trajectory concepts for reconstructing mechanically stress fields that are suitable for parametric analysis. Attempts have been made to include the
curvature of the lithosphere, complex geometries, and different rheologies for identification of potentially unstable regions and for quantifying the evolution with respect to tectonic impact. Such work has shown that the principal stresses are closely spaced near craton boundaries and that the vertical principal stress there is not the intermediate one.

Applying the same and additional ways of assessing the potential for unstable conditions in Sweden and Finland it has been concluded that the conditions respecting stability are not severe. The resolution power is limited, however, and identification of major discrete features of the commonly assumed one-cubic kilometre repository rock and extensive rock stress measurements in it are needed for estimating the risk of instantaneous or time-dependent slip along discontinuities of 3rd and lower order.

**Structural implications for earthquakes and large rock strain**

If a sufficiently large change in the regional stress field takes place the largest and weakest discontinuities react first. Those of 1st order that are critically oriented react by undergoing ductile shear strain but stronger parts, acting as asperities, break in a brittle fashion when the strain has become critically large. The breakage is associated with release of high energies, yielding vibrations and shearing that causes additional fracturing and reduction in strength, and transfer of stresses to the network of 2nd order discontinuities. The latter will thereby undergo shear strain that in turn activates those of 3rd order. The 4th order discontinuities in the rock mass are water-bearing by definition and have higher shear strength and are the last to react. A number of them intersect deposition holes and tunnels and slip along them can affect the buffer and canisters. This issue is of fundamental importance for estimating the probability of critically large shearing of the deposition tunnels and holes with clay-embedded HLW canisters.

Naturally, prediction of strain by use of mathematical models requires that the conceptual deformation model is relevant and that representative material parameter values have been found. For crystalline rock the structural constitution is characterized by a high frequency of discontinuities of all types and hence by a corresponding spectrum of strength. Irrespective of the comprehension of the rock investigation the assumed rock structure can never be validated and one has to be content with simplified models. Such a study has been made by use of analytical technique assuming the friction angle of 2nd order discontinuities is 10°, and that of the 3rd order fracture zones to be 15°, while it was assumed to be 25° of the 4th order fractures (cf. Figure 7), (Pusch, 2008). The calculations showed that the rotation of the stress field by 90 degrees generated shearing on the millimetre scale of the discrete fractures of 4th order, i.e. of the type that intersect deposition holes, while the 3rd order fracture zones were sheared by a decimetre and the 2nd order zones by about one meter. 1st order discontinuities, i.e. very large weak zones that were not included in the model, would deform by tens to hundreds of meters. In practice, rotations of this magnitude do not take place instantaneously but occur stepwise in conjunction with strong seismic events and intercontinental relative displacements.

The case is deemed significantly over conservative. However, at deglaciation of areas that have been covered by 3 km of ice rapid melting of the ice can create critical stress conditions and rather quick and large displacement of the earth crust as illustrated by Figure 8.

**Impact of repository construction on the performance of the nearfield rock**

Strain caused by redistribution of the stresses when excavating tunnels, drifts and shafts leads to high hoop stresses near the periphery of the openings and these stresses determine the stability of the openings and affect the groundwater flow into and along them. The distribution of stress and strain is strongly influenced by the rock structure, in particular by discontinuities of higher orders than 3. If the rock structure is changed by tectonic impact and by construction and exposure to heat related to the radioactive decay, the performance of the rock will change and thereby affect the isolating ability of the engineered barriers. Thus, the HLW canisters may be exposed to shearing and fail by slip along fractures that intersect the deposition holes.

![Image](image_url)

Fig.7. Assumed rock structure model for calculating shear strain of the respective elements. The spacing and persistence of the 3rd order discontinuities is 100 m in the model while the 4th order discontinuities have a spacing of 5 m and a persistence of 25 m.

![Image](image_url)

Fig.8. Aerial photo of major steep displacement along a 1st order discontinuity formed at deglaciation of northern Sweden less than 10000 years ago (“Falha Pärvice fault”). The height of the steep slope is up to 25 m. (Photo by Talbot)

The stress conditions in the rock around vertical deposition holes calculated by BEM technology (BEASY, 1996) are illustrated in Figures 9 and 10. The natural, primary rock stresses are 30 MPa in X-direction, 15 MPa in Y-direction and 10 MPa in Z-direction. The E-modulus was taken to be 105 MPa and Poisson’s ratio 0.3. The practical use of such calculations is that the factor of safety can be evaluated by comparing the theoretically derived stresses with the laboratory- and field-determined strength of the rock.

Figure 10 shows that the highest hoop stress is about 206 MPa, which is on the same order as the uniaxial compressive strength of ordinary crystalline rock (Table 3), implying a risk of failure in the form of spalling and fracturing in the rock around the deposition holes.
Breakage would take place at any time after construction and definitely when the rock temperature rises due to the radioactive decay. The stress conditions at the proposed repository site hence make its location unsuitable.

Experienced rock engineers can point out where and how failure can be expected in the course of repository construction by considering the orientation and interaction of 4th and lower order discontinuities but a number of potential failure planes are not visible. Calculation of the shear displacement along hidden discrete weaknesses can be made as illustrated in Figure 11, calling for examination of the rock walls by “impact echo” technique (Pusch, 2008) or similar for making sure that there are no such features. Otherwise the holes should be abandoned.

**Impact on the rock by blasting tunnels and holes – the EDZ**

Disturbance by blasting and stress changes of the rock around drifts and tunnels leads to continuous excavation-disturbed zones along them, called EDZ. The disturbance is caused by high pressure at detonations and by the stress changes caused by the removal of rock. The matter is of great practical importance and has been subject to several national and international studies [EUROPEAN COMMISSION, 2005; Deere et al., 1967].

The EDZ has strong impact on the structural constitution of the rock. It increases the porosity and causes stress relaxation of the peripheral part of the rock and therefore less risk of spalling than for bored rooms, and it increases the hydraulic conductivity very significantly to a distance of several decimetres from their peripheries. Careful blasting can reduce the depth of damage to a few decimetres except in the floor where it extends to about one meter even if careful blasting technique is employed. The importance of the rock structure is obvious in this context: the reflection of pressure waves and dynamic shear waves cause separation and relative movement of rock blocks along existing open and latent weaknesses. The nature of the EDZ of blasted drifts around drifts and tunnels is illustrated by Figure 12.

**Table 3. Typical unconfined compression strength of core samples (Pusch, 2008).**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Compressive strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>150-300</td>
</tr>
<tr>
<td>Gneiss</td>
<td>170-300</td>
</tr>
<tr>
<td>Diabase</td>
<td>300-500</td>
</tr>
<tr>
<td>Quartzite</td>
<td>200-500</td>
</tr>
<tr>
<td>Leptite</td>
<td>100-300</td>
</tr>
<tr>
<td>Shale</td>
<td>100-200</td>
</tr>
</tbody>
</table>

Two series of large-scale hydraulic tests have given detailed information on the hydraulic properties of the EDZ in granite. A drift with 20 m² cross section made by careful blasting and a length of more than three blast rounds was investigated by use of ventilation technique (Gale & Roleau, 1986), and, in a separate test, by forcing water to flow along the drift and in the normal direction (Börgesson et al., 1992, Liedtke et al., 1999). The general conclusion was that there were two EDZs: a blast-disturbed, damaged zone extending to 0.7 m depth from the tunnel wall, and a stress-induced disturbed zone extending from 0.7 to 3 m depth. Outside this distance the rock maintained its virgin hydraulic properties characterized by a conductivity of 3E-11 to 9E-11 m/s. The blast-disturbed EDZ had an average
The geological basis for disposal of HLW

The isotropic conductivity of 1.8E-8 m/s while the surrounding rock extending from 0.7 to 3 m had an axial conductivity of 3E-10 to 9E-10 m/s and a radial conductivity of 7.5E-12 to 2.3E-11 m/s, hence manifesting the formation of a “skin” zone. Shutting off the damaged part by constructing keyed-in concrete bulkheads with “O-ring” type dense clay can reduce the axial hydraulic conductivity of the EDZ to be only 10 times higher than that of the virgin rock.

Corresponding measurements of the disturbance caused by large tunnel boring machines have shown that the boring-induced EDZ is only a few centimeter deep (Pusch, 2008). However, its fine-fissured constitution makes it serve as an effective path for diffusional migration of water and cations, including possibly released radionuclides.

Inflow into backfilled underground rooms – a structure-controlled process

The detailed nature of the discharge of water from the rock into tunnels depends on the geometry of the inflow points (Figure 13). Observation of the distribution of inflowing water from tunnel walls has led to the conclusion that it preferentially follows intersections of fractures representing 4th order discontinuities. In backfilled drifts and tunnels water hence tends to penetrate the fill at distinct points, which have a spacing determined by the pattern of such fractures. Where the tunnel is intersected by a water-bearing fracture zone of 3rd order there can of course be significant inflow through its numerous fractures.

The frequency and spacing of inflow points controls the wetting rate of the backfill and determines, together with the inflow rate, whether critically high hydraulic gradients leading to piping and erosion can take place. Experiments with backfills consisting of loosely layered pellets of smectite-rich clay (bentonite) placed to form a moving slope in tunnels with point inflow of water has led to the conceptual model in Figure 14. It implies that channels are formed in the backfill from the inflow points for an inflow rate as low as 0.1 l/min already after about one day when the distance between the point and the slope is about 1 meter. The penetrating water flows downwards and is discharged at the foot of the slope, turning the fill into slurry.

One learned from this that backfilling operations must go on at a certain minimum rate to keep the distance between the advancing water and the moving slope sufficiently large, and that a bulkhead must have been installed at the planned outer end of the filling prior to the filling (Pusch et al., 2012).

Fig.12. Conceptual model of the creation of an EDZ along a blasted tunnel by hydraulic connection of local blast-induced EDZs and longitudinal natural fractures widened by stress changes. Major flow paths after filling the tunnel with material that is less conductive than the rock are represented by fat arrows.

Fig.12. Modelo conceptual para a criação de um EDZ ao longo de um túnel estilhaçado por conexão hidráulica de EDZ localmente induzidos e fracturas naturais longitudinais alargadas por variações de tensão. Os principais percursos do fluxo após o preenchimento do túnel com material menos condutivo que a rocha estão representados por setas gordas.

Fig.13. Schematic drawing of the cross section of a typical major flow path formed by intersecting fractures of 4th order.

Fig.13. Desenho esquemático da seção de um típico percurso de fluxo formado pela interseção de fracaturas de 4ª ordem.

Fig.14. Early wetting for different inflow rates from a spot. Left: Uniform diffusive wetting of the pellet fill for inflow rates <0.1 l/min. Right: Rapid wetting by flowing water.

Fig.14. Encharcamento precoce para diferentes taxas de fluxo a partir de um ponto. Esquerda: Encharcamento uniforme difusivo da bolsa com taxas de influxo de <0.1 l/min. Direita: Rápido encharcamento por água corrente.

The aim of finding out what the actual spacing of inflow points and inflow rates are for planning a backfilling operation can be achieved by using fracture mappings and recording the average inflow into isolated tunnel segments. A practical case of constructing a physical model of hydraulically active discontinuities in a 90 m long TBM-bored drift at 400 m depth with 5 m diameter is shown in Figure 15. The position of the points of intersection of the fractures representing 4th order discontinuities, which make up 4 major fracture sets, can be directly counted. Knowing the total inflow of water per time unit one can calculate the average inflow per point. For the distance 3560-3580 m with 6 inflow points the daily inflow was 1500 l corresponding to about 0.2 l/min for the individual inflow points. This would not cause piping if the backfilling rate is at least 2 m
per day, while the inflow of 7500 l/day for the distance 3585-3600 m in 10 points, i.e. about 0.5 l/min per point, would not make backfilling of clayey material possible at all.

4. Discussion and conclusions

Recent attempts to work out concepts for deep geological disposal of highly radioactive waste from nuclear reactors consider the host rock to be a major barrier to transport of radionuclides that may possibly be released from the repository to the biosphere. Despite the very limited information on the constitution and properties of the large rock mass sophisticated hydraulic modeling is made for calculation of groundwater flow and transport of dissolved species, largely disregarding from possible long-term impact of tectonic movements and seismic events on the transport paths, and neglecting that the rock stresses will cause spalling and fracturing of the rock immediately surrounding the waste containers. The role of excavation disturbance of the rock is not fully realized by the modelers and the entire problem of foreseeing the evolution of groundwater flow in the “near-field” and “far-field” in a time perspective that includes at least one glaciation event has not yet been adequately solved. At present, one must rely on the engineered barriers for safe disposal of highly radioactive waste and take the rock to serve as a mechanical protection of the clay-embedded waste containers, i.e. the “chemical apparatus”.

References


