

## **SKB TR-11-01**

### **Long-term safety for the final repository for spent nuclear fuel at Forsmark**

#### **Main report of the SR-Site project**

#### **Volume II**

In the earlier distributed report, there are errors that have now been corrected. The corrected pages 294, 318, 330, 334, 337, 347, 387, 417, 424, 430, 436, 454, 459, 463, 512, 525, 526, 529, 537, 538, 540, 541, 542, 543 and 548 are enclosed. The changed text is marked with a vertical line in the page margin. An updated pdf version of the report, dated 2011-10, can be found at [www.skb.se/publications](http://www.skb.se/publications).

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## 10.2.2 Mechanical evolution of near-field rock due to excavation

The rock mass at repository depth is under a pre-stressed condition, namely the in situ rock stress. Repository excavation, i.e. removal of rock, creates a localized readjustment of the in situ stresses. This raises several rock mechanics concerns for the construction work, such as the risk of breakouts into excavated volumes, spalling and/or key block instability. These engineering-related rock mechanics issues are evaluated within the framework of the repository design work and reported in the design report /SKB 2009b/, and are to a large extent not of importance for long term safety. However, as further discussed in Chapter 5 and fully assessed in the **Underground openings construction report**, the design and construction of the underground openings must follow specific design premises provided from a long term safety perspective /SKB 2009a/.

The following mechanical processes related to the excavation and the open phase could have potential safety implications (the safety functions refer to Figure 10-2):

- Development of an Excavation Damaged Zone (EDZ) and other impacts on rock permeability (safety function R2ab, see Figure 10-2).
- Spalling, (safety function R2b and also safety functions of the buffer that either directly or indirectly depend on buffer density).
- Reactivation of fractures (safety function R2ab and R3b).
- Induced seismicity (safety function R3bc).

These issues are assessed in the **Underground openings construction report** and the resulting initial state is summarised in Section 5.2.3. However, for transparency the safety relevant conclusions are repeated in the following subsections, together with the assessed implications for the safety functions.

### **Deposition hole EDZ and spalling**

Drilling of deposition holes is not judged to result in any significant damages to the surrounding intact rock. As stated in Section 5.2.3 and in the **Underground openings construction report**, Chapter 6, findings from a comprehensive literature study /Bäckblom 2009/ suggest that for mechanical full face down-hole drilling techniques in competent rock the depth of damaged zone (EDZ) is limited to less than a few centimetres in the rock surrounding the deposition hole. The hydraulic conductivity in such a zone is in the order of  $10^{-10}$  m/s or less. Hence there is high confidence that competent rock conditions prevail for the reference design and consequently that the EDZ axial transmissivity in deposition holes would be less than  $10^{-10}$  m<sup>2</sup>/s. However, the magnitude of the connected effective transmissivity may be altered due to occurrences of spalling.

If the initial, pre-excavation, stresses are sufficiently high, spalling may occur during the operational phase in response to the stress redistribution caused by excavation. The **Underground openings construction report** states, based on analyses by /Martin 2005/ and a three dimensional elastic stress analysis, presented in the repository design report /SKB 2009b/, that in the case of the “most likely” stress model, some 100–200 deposition holes (out of 6,000) would experience a spalling depth (overbreak) that exceeds 5 cm, provided the deposition tunnels are aligned between 0 and 30 degrees to the maximum horizontal stress. Due to uncertainty in stress an alternative, “unlikely maximum” stress model is also considered. For the “unlikely maximum” stress model, the deposition tunnel must be aligned parallel to the maximum horizontal stress, but the number of deposition holes that can sustain a spalling depth in excess of 5 cm is approximately the same.

If spalling were to occur prior to waste emplacement, the current reference method stated in the **Underground openings construction report**, would be to remove loose rock debris from localised spalling on the rock walls. Larger overbreak would need to be filled with, for instance, pieces of bentonite or with bentonite pellets before or during installation of the bentonite buffer. The ultimate contingency action is to reject the deposition hole. Thereby it should be ensured that deposition holes will always have negligible EDZ prior to waste emplacement. In conclusion, there are no safety related impacts of the few cases of spalling prior to canister emplacement expected provided the action envisaged in the **Underground openings construction report** is implemented.

Hydraulically, the evolution is dominated by upconing and drawdown effects of the repository excavation. The hydrogeology studies presented in Section 10.2.3 show that salinities generally will decrease at repository level due to the drawdown of shallow waters, apart from a few locations where salinities slightly increase due to upconing. The inflow to the repository is very small, but it should be noted that groundwater will seep into the already plugged deposition tunnels, thus affecting the potential for piping and erosion of the buffer and the backfill in these tunnels.

The drainage of water into the opened part of the repository affects the hydraulic evolution of the buffer, backfill and plug in already deposited tunnels. The plug needs to be able to limit the flow of water out from the backfilled tunnel, primarily to minimise the effect of piping in the buffer and backfill. Modelling has shown that it will take 5–20 years to saturate the bentonite seal within the plug. This means that either the plug/rock interface or the pellet filling in the seal need to limit the flow during that period. Precise requirements on the seal capacity are not yet defined but the plug design will under all circumstances be adjusted to meet the requirements when specified. Since the only function of the plug is to ensure the initial state before closure, failed plug performance is not assessed in SR-Site.

- Piping and subsequent water flow from a fracture into a deposition hole and further out into the deposition tunnel cannot be excluded if the inflow rate is higher than the rate of water absorption of the buffer material, since the pellet filling and the bentonite blocks cannot stop the water inflow until the deposition holes and the tunnel are water filled and the hydraulic gradient is taken by the end plug. Erosion tests have shown that the dry mass of eroded bentonite can be modelled as a function of the total volume of inflowing water.
- The calculations of the swelling and homogenisation of a half torus resulting from erosion show that the swelling yields a strong decrease in density and swelling pressure in the eroded volume due to the friction in the bentonite. About 100 kg of dry bentonite may be lost due to erosion without jeopardizing the function of the buffer. This situation is handled by avoiding deposition holes with too high an inflow, see Section 5.2.1, and is not further assessed in SR-Site. However, the uncertainty in the assessment of the eroded volume needs to be considered when revising the design premises for acceptable inflow to deposition holes, see further Section 15.5.

During the excavation/operational phase, the chemical evolution mainly arises from the disturbance to the natural conditions caused by the presence of the repository. According to the results presented in Section 10.2.5, the following conclusions can be drawn.

- There is a large uncertainty in the detailed salinity distribution around the repository. However, the salinity will not become so high or so low as to affect the performance of the repository during this period or when considering its future evolution. The distributions of salinity, pH and other groundwater characteristics obtained from the modelling of the temperate conditions at 2000 AD, described in Section 10.3.7, is wide enough to include the small changes caused by the operation of the repository.
- A short alkaline pulse in the groundwater from low-pH cement, shotcrete and concrete is likely to form, but its effects will be negligible.
- An increased precipitation of calcite and iron(III)-oxyhydroxides will occur at the tunnel wall during operations, but this process is evaluated as being of no consequence for the performance of the repository.
- Organic stray materials will be consumed by microbes, with the main effects being an increased rate of oxygen consumption and possibly also of sulphate reduction. The largest pool of organic carbon in the repository is the organic matter included in the bentonite. This could contribute to canister corrosion if it could be made available for microbial sulphate reduction. This is considered in the canister corrosion assessment during the initial temperate period, see Section 10.3.13.
- An increased formation of colloids during the excavation and operational phases will not affect the performance of the repository in the long-term, because the colloid concentrations will quickly resume their natural values.
- Oxygen left in the repository will be consumed by either chemical processes or microbes; the majority of the oxygen in the backfill, which has the largest pore volume in the deposition tunnels, will react and thus not diffuse into the buffer and reach the surface of the canister.
- Canister corrosion depths from the atmospheric and initially entrapped oxygen are expected to be less than 500 µm at the most, and will thus have a negligible impact on the minimum copper coverage of the canisters.

The following mechanical processes related to the initial temperate period after repository closure, could have potential safety implications.

- Reactivation of fractures in the near field due to thermal load, including fracture aperture reductions due to temperature increase expanding the intact rock, that could affect the mechanical stability (safety function R3bc, see Figure 10-2) and the fracture transmissivity and thus the transport resistance in the near-field rock (safety functions R2ab).
- Reactivation of fractures in the far field that could affect fracture transmissivity and thus the transport resistance (safety function R2a).
- Reactivation due to the crustal strain resulting from the mid Atlantic ridge push that could affect the mechanical stability of the deposition holes (safety function R3bc).
- Fracturing of the rock that could affect the deposition hole geometry (safety function Buff1) and migration between buffer and rock (related to safety function R2a).
- Potential for creep deformation that could affect deposition hole geometry (related to safety functions Buff3 and Buff6). Here the term creep is also used for cases in which the mechanical load is not constant over time, i.e. when the shear strain successively relaxes the stresses.

These issues are assessed in the following subsections.

## Modelling approach

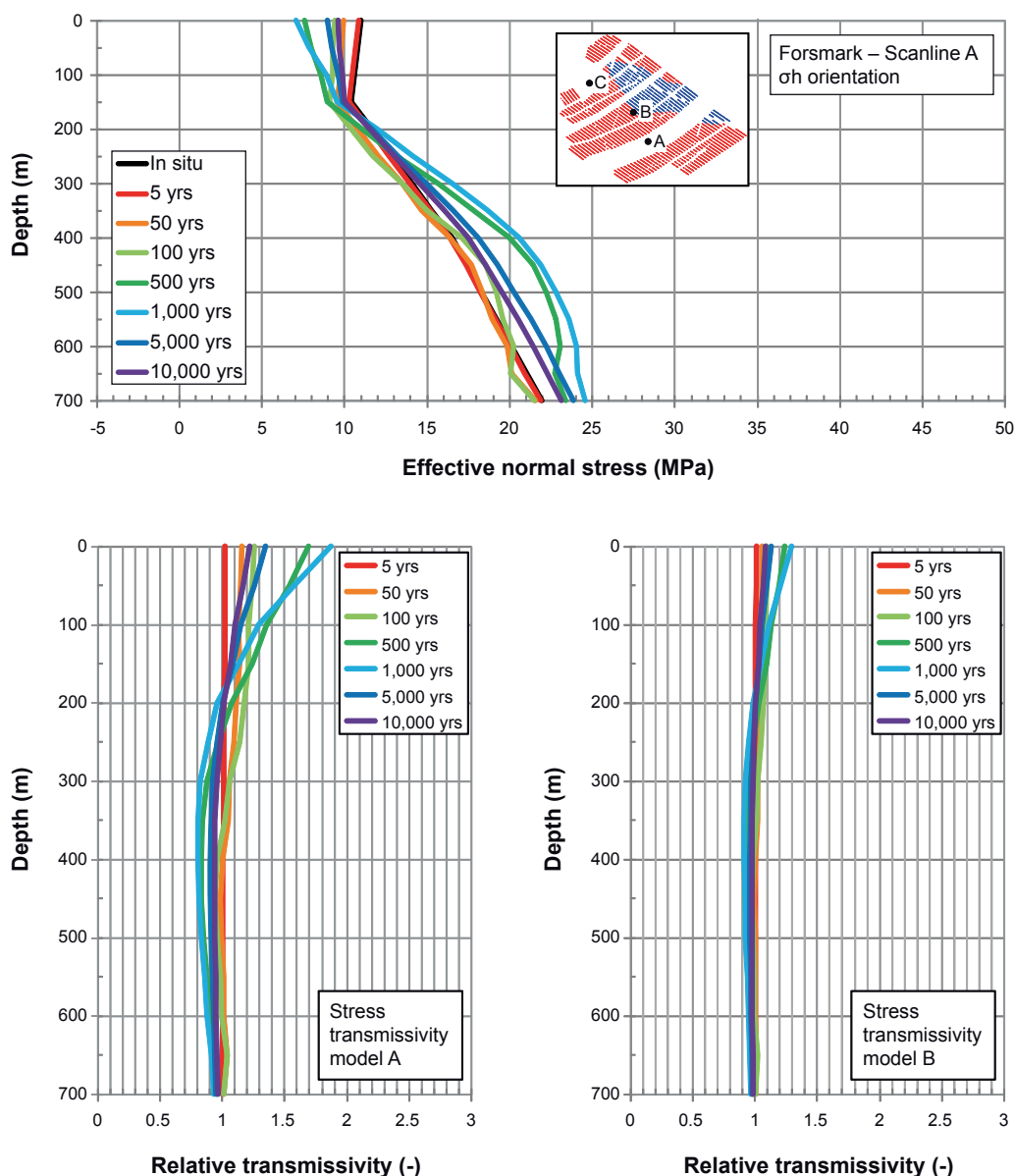
Most of the above issues are assessed by integrated numerical modelling /Hökmark et al. 2010/ applying the distinct element code 3DEC (3 Dimensional Distinct Element Code) /Itasca 2007/ on a large scale and on near-field models. This modelling produces stress changes resulting from the thermal (and later glacial) loads. These stress changes, in turn, are used to assess potential changes in fracture or fracture zone transmissivity by assuming certain relationships between stress change and transmissivity.

The large-scale model is represented by rectangular blocks with dimensions 8 km·7.4 km·3 km, see Figure 10-17. Average values of the thermo-mechanical properties judged to be relevant in the entire modelled domain are used to represent the properties of the rock mass as further specified in the **Data report**, Section 6.4. The heat sources are positioned in the models according to Layout D2, where the loss of canister positions is assumed to be uniformly distributed across the repository region. Boundary conditions for the subsequent near-field modelling are obtained from the displacements on pre-defined cut-planes representing the near-field model boundaries and are evaluated as the expansion/contraction relative to the centre of the near-field model as a function of time.

Two types of and sizes of near-field models are used:

- One tunnel segment with seven heat generating canisters (for spalling analyses), but with only three of the deposition holes explicitly included. Model dimensions are 40 m (across tunnels) and 50 m (vertically), see Figure 10-18.
- Five tunnel segments each with 33 potential canister positions (shearing, normal stress variations and transmissivity changes of fractures). None of the deposition holes are explicitly included. Similarly to the approach taken by /Hökmark et al. 2006/ and /Fälth and Hökmark 2007/ the fracture system is stylised considering a model in which the fracture orientations are based on site-data in fracture domain FFM01 /Fox et al. 2007/ and a model with one fracture orientated such that the potential for shear failure is large, see Figure 10-19. Model dimensions are 200 m (across tunnels) and 200 m (vertically).

Based on the transmissivity data for fracture domain FFM01 at Forsmark /Follin et al. 2007b/ and fracture normal stiffness data given in the **Data report**, /Hökmark et al. 2010/ apply two different models for the relation between stress and transmissivity changes, see Figure 10-20. As further discussed in the **Data report**, the strength of the hydromechanical coupling is highly uncertain, but it is judged that the range of these models captures, or at least overestimates, this coupling.



**Figure 10-21.** Top: Effective stress along a scan-line in the direction of  $\sigma_h$ . Here compression is positive. Bottom: Relative transmissivity of fractures perpendicular to  $\sigma_h$ . From /Hökmark et al. 2010, Figure 6-21/.

analytical expression. The slip movement is accompanied by a normal stress increase, due to the heat load, which means that the transmissivity might decrease rather than increase. It should also be noted that the slip, and transmissivity impacts, will be much less for fractures with other orientations.

In conclusion, the transmissivity changes induced by the thermal load are judged too small to require any further consideration in the far-field hydrogeological analyses.

### Reactivation of near-field fractures

Results from the intermediate scale near-field model suggest that during the thermal phase the normal stresses for the site specific fracture orientations generally increase, leading to small reductions of the transmissivity of the modelled fractures. Also, the transmissivity increase close to the tunnel resulting from the excavation, see Figure 10-6, is much reduced compared with that during the period of excavation. There may be regions very close to the openings where local transmissivity effects could be significant, for instance because of thermally induced shear displacements along fractures in very low compression. According to /Hökmark et al. 2010/ these effects do, however,

If spalling occurs and a notch forms, the stress adjustments that can occur at the notch tip may cause additional time-dependent/creep deformations. The monitoring of the unconfined open notch in the APSE Experiment showed that the majority of the new displacements occurred in the existing notch /Andersson 2007/. /Martin and Kaiser 1996/ reported that the displacements for an unconfined spalled zone/notch in the AECL Mine-by Test Tunnel Canada were monitored for a 13 day period and that the creep related displacements amounted to between 0.6 and 1.4% of the total displacements measured over that period. They concluded from their field experiment that changes in the measured displacements over time generally can be attributed to changes in boundary conditions and that these time-dependent displacements occur in the unconfined damaged zone around the test tunnel. As shown by the APSE experiment a small confining stress is often sufficient to suppress spalling /Andersson 2007/. When the spalled notch is confined, any time-dependent deformations are expected to be insignificant, compared with the deformations that formed the notch.

It can also be noted that the effects of fracture creep, in terms of fracture displacement under constant shear load because of time-dependent material strength properties, can be estimated using the modelling approach for fracture reactivation described in /Hökmark et al. 2010/. This would be the same as those of a slow decrease in fracture shear strength, i.e. some additional stress relaxation and a corresponding amount of additional movement. Even if the strength is reduced to zero over the entire fracture plane, only very minor fracture displacements would occur.

Creep deformation and related issues like “sub-critical crack growth” is, therefore, not further considered in SR-Site.

#### **Identified uncertainties and their handling in the subsequent analysis**

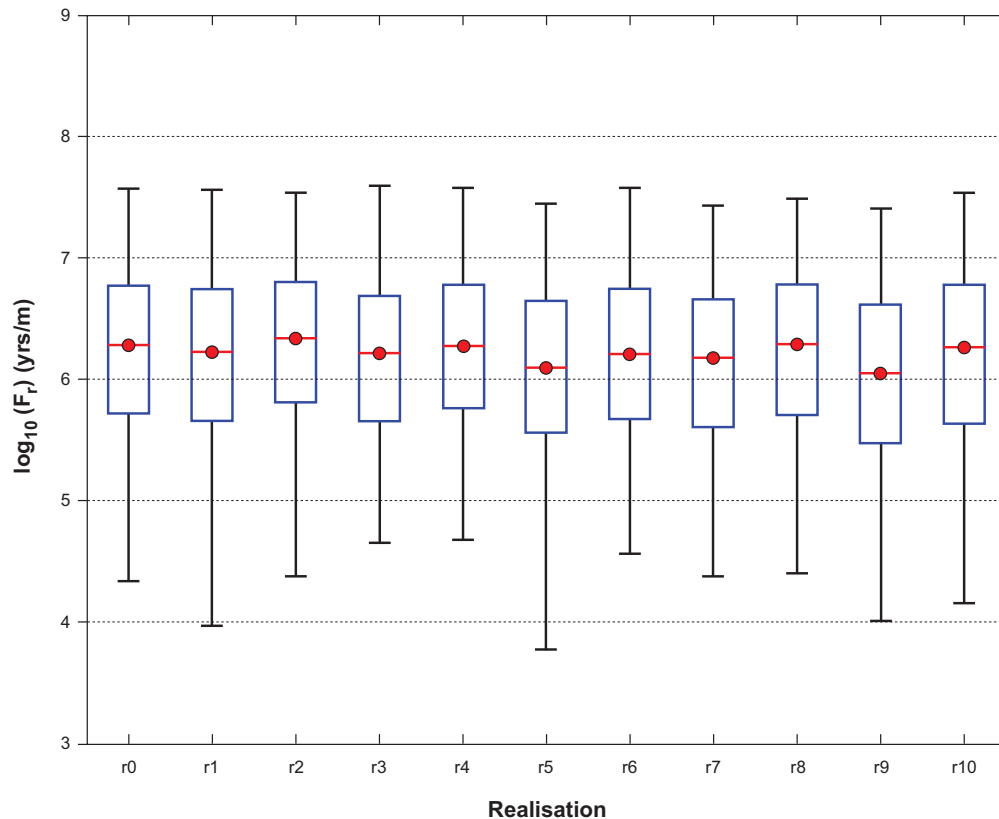
The discussion above can be used to draw a set of conclusions regarding the uncertainties and their subsequent handling in the SR-Site analyses in relation to the mechanical evolution during the initial temperate period.

- *Reactivation of fractures in the near field* due to thermal load that could affect the mechanical stability and the fracture transmissivity in the near-field rock are excluded from further analysis since the calculated impacts on fracture transmissivity during the heating phase are small, and very local to the deposition tunnel.
- *Reactivation of fractures in the far field* that could affect fracture transmissivity is excluded from further analyses since the calculated transmissivity changes induced by the thermal load are judged too small to require any further consideration in the far-field hydrogeological analyses.
- *Reactivation due to tectonic compression* that could affect the mechanical stability of the deposition holes (safety function R3a) cannot be totally ruled out even during the temperate period. This is further assessed in Section 10.4.5.
- *Fracturing of the rock, i.e. thermally induced spalling*, is likely to occur but the counter pressure exerted by bentonite pellets in the slot between buffer and rock wall, may suppress the spalling, or at least keep the spalled slabs in place and minimize the hydraulic transmissivity of the spalled damage zone. A set of distinct calculation cases, assuming no spalling or spalling in all deposition holes, are propagated for further assessment. This does not mean that efforts to handle and mitigate thermally induced spalling should not continue since suppressing the spalling will enhance this safety function. The potential for spalling may also depend on the deposition sequence, but only for very specific ones. Nevertheless this may need consideration for the detailed design of deposition areas, see further Section 15.5.15.
- There is no potential for *creep deformation* that significantly could affect deposition hole geometry, allowing the exclusion of the phenomenon.

### **10.3.6 Hydrogeological evolution**

In SR-Site, the hydrogeological evolution during the temperate period after repository closure involves two distinct time intervals. The first is that for saturation of the repository once pumping of the open tunnels has stopped. The subsequent time interval deals with the evolution of the saturated repository up till the start of the next glacial period. The actual impacts primarily depend on the permeability





**Figure 10-31.** Box and whisker plots of flow-related transport resistance ( $F$ ) for the Q3 path in the hydrogeological base case realisation ( $r0$ ) and the 10 stochastic realisations of the HCD and HRD ( $r1$  to  $r10$ ) for the particles successfully reaching the model top boundary released at 2000 AD. The statistical measures are the median (red), 25th and 75th percentile (blue box) and the 5th and 95th percentile (black “whiskers”).

In order to assess the effect of branching along the flow paths on the advective travel time and flow-related transport resistance, multiple particles (ten) have been released per start point in the particle tracking. Only the 25 percent of start points with highest Darcy flux were used in the comparison. The ten particles choose different flow paths due to a stochastic choice (weighted by flow rate) at each fracture intersection. The results indicate that the branching has negligible effects on the ensemble statistics of the analysed performance measures.

### Penetration of dilute water

In principle, the future groundwater chemistry is provided by the regional scale groundwater flow simulation reported above. However, the regional scale simulation was terminated at 12,000 AD and, furthermore, has a fairly coarse discretisation which does not allow an assessment of the groundwater chemistry evolution on a deposition hole scale. Thus, an alternative assessment of the evolution of the groundwater chemistry, and specifically the potential for penetration of dilute water, is made since dilute groundwater may cause erosion of the buffer and the backfill.

In order to assess the potential for penetration of dilute water, a simplified approach is adopted. An injection of meteoric water along those recharge pathways that originate close to the surface within the regional-scale model is considered; it is assumed that the infiltrating water has zero salinity. Note that this is a pessimistic assumption, as discussed in Section 10.1.3. Also, in this simplified calculation, it is assumed that the matrix and fracture water salinity is in equilibrium at the start of the simulations; the relevance of this assumption is also discussed in Section 10.1.3. The flow field and recharge flow paths of year 2000 AD are used. Along the flow paths, the only mitigating process considered is the out diffusion of matrix water affecting the penetration of the meteoric water front. For each deposition hole, the time required for the groundwater salinity to fall below ten percent of the initial water concentration is calculated. Figure 10-32 shows the distribution of these times for

**Table 10-5. Total allowed loss for the case illustrated in Figure 10-60.**

$\phi$ (°)	Total loss (t)
10	430
20	220
30	150

This means that the distance assumed between the canister and the backfill is 1.5 m as presented in Figure 5-16 and not the 2.5 m illustrated in Figure 10-60. It is also assumed that the friction angle is the same in the buffer and the backfill and that the mass loss in the backfill occurs directly on top of the canister and that the backfill is lost to a vertical fracture. A mass loss further away in the tunnel or to a sloping fracture would mean that additional backfill could be lost.

It is reasonable to assume that the friction angle will be about 20° for these conditions, since the swelling pressure is lower than 100 kPa /Börgesson et al. 1995/. This means that a total of 220 tonnes of backfill can be lost before the swelling pressure on top of the canister drops to 100 kPa.

Loss of backfill from erosion is important for the properties of the buffer in the deposition hole, but is not expected to have any significant importance for the transport properties itself. There will be a local volume with low swelling pressure and high hydraulic conductivity. However, the main part of the tunnel volume will be unaffected.

#### Potential for advective conditions

Advective conditions in the buffer can occur if the hydraulic conductivity is sufficiently high. The buffer function indicators prescribe a hydraulic conductivity of  $10^{-12}$  m/s and a swelling pressure of 1 MPa to rule out advection in the buffer. These values do, however, have some safety margins included in them.

/Neretnieks 2006b/ calculated the conditions under which water is drawn into a deposition hole. He concluded that even for a rock fracture with a very high flow rate (transmissivity  $10^{-6}$  m<sup>2</sup>/s and hydraulic gradient 0.01), a buffer conductivity of around  $3 \cdot 10^{-6}$  m/s suffices to prevent advection and causes the water in the fracture to flow around the buffer as if it were impervious. Such conductivity corresponds to a dry density well below 500 kg/m<sup>3</sup>. However, to ensure that the self-sealing ability is maintained and no channels or pipes will be formed, a certain swelling pressure is also required. The minimum swelling pressure needed will be about 100 kPa. This is based on laboratory investigations in which piping has been observed at ~60 kPa /Karnland et al. 2006/. This value is most likely still pessimistic, since the gradients at the site are expected to be very low. However, the effect on the accepted mass loss will be relatively small. To ensure this for all expected groundwater compositions, a minimum dry density of 1,000 kg/m<sup>3</sup> is required (Figure 5-14). This corresponds to a void ratio of 1.75. As seen in Figure 10-59 this requirement is still met in almost the entire buffer diameter when two entire bentonite rings are omitted, corresponding to a dry mass loss of 2,400 kg.

For the case when the buffer erodes by colloid formation, the mass loss may be more local compared with the case in which entire blocks are omitted and it is more appropriate to consider the corresponding limit for losses over typically half the circumference, i.e. 1,200 kg, which would also cover the situation when the loss occurs closer to the centre of the canister. This value includes some pessimism since homogenisation in the horizontal direction is neglected. However, at higher mass losses, the swelling pressure cannot be guaranteed and advection in the buffer has to be considered. This is further elaborated for the case of buffer erosion in Section 10.3.11.

For the case when mass loss occurs mainly in the tunnel and only backfill material is lost, a maximum loss of 220 tonnes of backfill can be allowed before advective conditions have to be considered in the buffer in the deposition hole. However, loss of backfill by erosion does not mean that the hydraulic conductivity of the entire tunnel will be affected.



**Table 10-10. Compilation of results from the cases presented in /Åkesson et al. 2010a/. The calculations with names beginning with Plug1 have bentonite backfill on both sides of the plug while calculations with names beginning with Plug2 have crushed rock outside the plug. Suffix -2 refers to calculations with the high dry density  $\rho_d = 1,600 \text{ kg/m}^3$  and high swelling pressure of the bentonite backfill, while the names without suffix refer to calculations with the low dry density  $\rho_d = 1,450 \text{ kg/m}^3$  and low swelling pressure.**

Calculation	Displacements (m)		Maximum void ratio	Minimum swelling pressure (MPa)	Remarks
	Backfill1/ Plug	Backfill2/ Plug			
Plug1	0.03–0.07	–(0.03–0.07)	1.0	2.0	Locally at corner
Plug1b	0.15–0.27	–(0.15–0.27)	1.1	1.3	
Plug1-2	0.08–0.17	–(0.08–0.17)	0.86	5.7	
Plug1b-2	0.30–0.58	–(0.30–0.58)	0.99	3.0	
Plug2	0.10–0.15	0.05–0.07	1.1	1.7	Locally at corner
Plug2b	0.35–0.50	0.20–0.28	1.2	0.8	
Plug2-2	0.24–0.32	0.13–0.17	0.98	3.0	
Plug2b-2	0.70–1.05	0.40–0.58	1.2	1.0	

### **Canister sinking**

Apart from the few deposition holes losing buffer through colloid release, as assessed in Section 10.3.11, the buffer in other deposition holes will not be affected by any processes that may alter its swelling properties in a way that the swelling pressure would sink below the value needed to retain the canister in position ( $P > 0.2 \text{ MPa}$ , see Section 8.3.2). Furthermore, in deposition holes losing buffer due to colloid sol formation, creation of advective conditions would occur long before the canister sinking could happen, making this issue irrelevant also for these cases.

### **Osmotic effects on the buffer and backfill**

According to Table 10-6, the maximum chloride concentration of any time frame is  $< 0.4 \text{ M}$  at repository level in the Forsmark groundwater. As seen in Figure 5-14 this is not expected to have any impact on the properties of the buffer material. This conclusion is valid for the entire repository evolution period.

### **Identified uncertainties and their handling in the subsequent analysis**

The various cases described in this section show that the chemical conditions in the buffer and the backfill are rather stable and no dramatic changes of the geochemical conditions can be expected. The expected conditions in the Forsmark groundwater (Table 10-6) are well within the range of of the parameters used in the sensitivity study for all future evolutions. As seen in the right side of Figure 10-65 the buffer (MX-80) is expected to have about equal populations of sodium and calcium in the exchanger for a typical Forsmark groundwater. The sensitivity study presented in Table 10-8 shows a range of 7–84% for the calcium population, but the minimum and maximum values in the range are both for Ca/Na ratios that are far away from what is expected in the Forsmark water for any condition (Table 10-6).

The effect of a degraded bottom plate on the mass transfer resistance in the near field is considered in SR-Site. However, the impact is less than the impact from assuming spalling in the deposition hole and this effect is thus covered by the assumption of spalling in all deposition holes. However, if spalling can be avoided and if the bottom plate is intersected by a fracture it will be the main transport path. In such a case the mass transfer resistance will be much lower than in an “ideal” case where the buffer is in contact with the rock in the bottom of the deposition hole. A thick, compressible bottom plate may lead to loss of density to a level below the design target of  $1,950 \text{ kg/m}^3$  in the bottom of the buffer. This shows that the current design of the bottom plate requires further consideration, see Section 15.5.10.

The model predictions indicate that the durability of backfill materials is not expected to be affected by the potential alkaline plumes developed from concrete alteration of the plug. Hence, the effect on the backfill properties will be small and can be neglected in the subsequent analysis. Also calculations show that the disintegration of the plug, which means that the backfill could then swell into the voids created, has no detrimental effect on the backfill above the first deposition hole and no restrictions on the location of the first deposition hole are needed.

## Advective conditions in the deposition hole

Corrosion under advective conditions in the deposition holes is assessed in Section 10.4.9. According to Section 10.3.11 no deposition holes will lose so much buffer mass by colloid release due to dilute groundwaters such that advective conditions must be assumed during the initial temperate period. (Even if such conditions were to occur, it is shown in Section 10.4.9, that the corrosion is not fast enough to create any failures of the copper shell during the first 100,000 years.)

## Summary of copper corrosion analysis

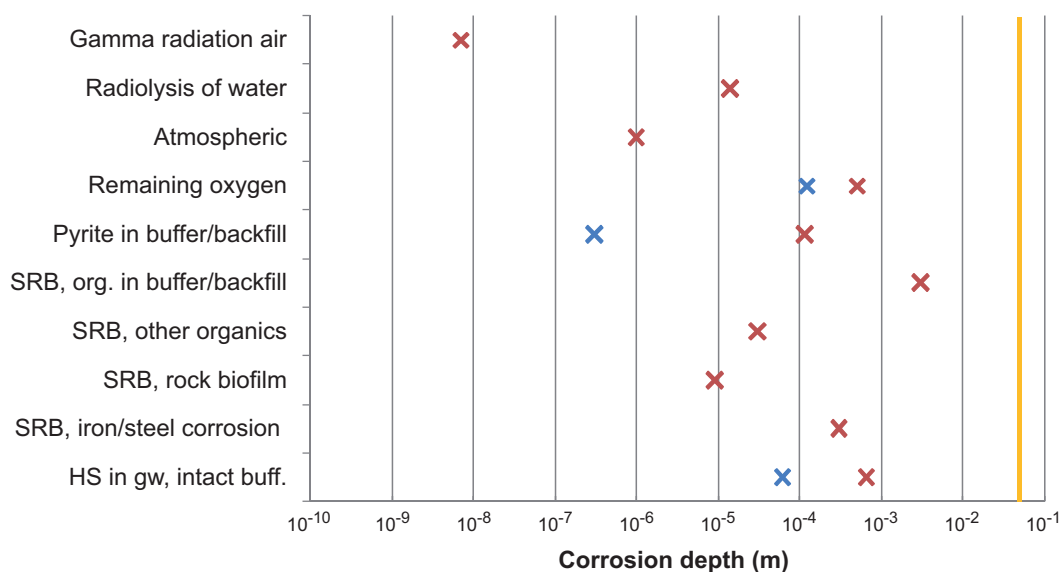
For the corrosion processes analysed for the initial temperate period, the corrosion depth is much smaller than the copper shell thickness. This is the case also for an assessment time of  $10^6$  years, as illustrated in Figure 10-88. Several processes give corrosion depths less than 100  $\mu\text{m}$ , and no processes give corrosion depths larger than a few mm. The corrosion depths from the different processes should not simply be summed up as their combination requires a far more detailed chemical analysis (as well as statistical analysis regarding the flow and sulphide distributions), but, even if they are cautiously added, the sum is still less than 5 mm.

## Identified uncertainties and their handling in the subsequent analysis

The following conclusions are reached regarding copper corrosion during the temperate period.

- The total amount of copper corrosion during the excavation and operational phases and the first 1,000 year period can be estimated to be less than 1 mm. The largest contribution to this estimate comes from the initially entrapped oxygen.
- Copper corrosion by contaminants in the buffer, backfill or groundwater does not pose a threat to canister integrity for the initial temperate period. Even during the one million year overall assessment period, expected corrosion of the canister for an assumed temperate climate would cause corrosion depths of the order of a few millimetres, even for the most unfavourable deposition positions at Forsmark.
- No deposition holes will lose so much buffer mass by colloid release due to dilute groundwaters such that advective conditions must be assumed, meaning that corrosion under advective conditions can be ruled out during the initial temperate period.

Corrosion failure will thus not occur during the initial thermal period.



**Figure 10-88.** Estimates of corrosion depth from different corrosion processes conceivable in the repository, here shown for an assessment time of  $10^6$  years. None of these processes causes penetration of the copper shell. Red crosses represent pessimistic assumptions, whereas blue crosses represent more realistic assumptions (where calculations are available). The yellow line indicates the copper thickness of 5 cm.

### 10.3.15 Summary of the first 1,000 years after closure

The heat from the spent fuel results in a fast temperature increase in the buffer, with peak temperature occurring some 5–15 years after deposition, followed by a slow reduction of the temperature due to the decay of the heat source. The analyses presented in Section 10.3.4 show that there is an adequate margin to the peak temperature criterion for the buffer, even when the spatial variability of the rock thermal properties is taken into account and with other data essential for computing the result chosen pessimistically. This conclusion is valid provided there is thermal management of the disposal sequence, such that the influence of already deposited canisters would not unduly affect the thermal evolution of canisters deposited later, see also Section 15.5.15. Such management is judged fully feasible and there is no need to consider a situation with a buffer above the peak thermal criterion in SR-Site.

The mechanical evolution of the host rock is dominated by effects of the thermal load from the canisters and, to a minor extent, the developing swelling pressure from the buffer and the backfill. The long-term impact of the rock stress field need also to be taken into account. According to Section 10.3.5, the following conclusions concerning the mechanical evolution can be drawn.

- *Reactivation of fractures in the near field as well in the far field* due to thermal load that could affect the mechanical stability and the fracture transmissivity in the rock are excluded from further analysis since the calculated impacts on fracture transmissivity during the heating phase are small, and very local to the deposition tunnel.
- *Reactivation due to ongoing Mid-Atlantic Ridge push* that could affect the mechanical stability of the deposition holes (safety function R3a) cannot be totally ruled out even during the temperate period. According to the earthquake analysis presented in Section 10.4.5, on average between  $9.3 \cdot 10^{-6}$  and  $2.2 \cdot 10^{-5}$  canisters may be sheared 50 mm or more due to earthquakes within the 1,000-year time frame.
- *Fracturing of the rock, i.e. thermally induced spalling*, is likely to occur but the counter pressure exerted by bentonite pellets in the slot between buffer and rock wall, may suppress the spalling, or at least keep the spalled slabs in place and minimize the hydraulic transmissivity of the spalled damage zone. A set of distinct calculation cases, assuming no spalling or spalling in all deposition holes, are propagated for further assessment. The potential for spalling might to some extent depend on the deposition sequence and other aspects of the design, see further Section 15.5.15.
- Literature evidence suggests that there is no potential for *creep* deformation that could significantly affect deposition hole geometry, allowing the exclusion of the phenomenon from the safety assessment.

Analyses of the hydraulic evolution of the system indicate that after repository closure a rapid initial inflow is followed by an asymptotic regime where the inflow gradually decreases. It will take several hundred of years for the repository to reach full saturation.

Detailed regional and repository scale groundwater flow analyses for the saturated host rock indicate that the Forsmark site has favourable properties in terms of performance measures related to groundwater flow and transport, using either of the models. Specifically, the transport resistance of the host rock, the so called *F*-factor, ranges between  $10^4$  and  $10^9$  y/m depending on the spatial location, and about 90% of all potential deposition holes have *F* values above  $10^6$  y/m. Distributions of Darcy fluxes and equivalent flow rates for use in subsequent analyses have also been obtained and show favourable properties. It can be noted that at least 70% of all potential deposition holes are not connected to any water bearing fractures, which implies that the hydraulic contact with these holes primarily is by diffusion to the EDZ (if it exist) and to the deposition tunnel. The models also yield salinity distributions and handle mixing of different water types yielding concentrations of other relevant non-reacting components of the groundwater. All these results are propagated to subsequent analyses of engineered barrier performance and radionuclide transport.

The analysis of the evolution of the geochemical conditions at the site has resulted in the following conclusions.

- Anoxic conditions are expected to be re-established shortly after closure and will continue for the whole temperate period following the closure of the repository, in spite of the increasing proportion of meteoric waters with time.

## Can3. Withstand shear loads

The canister is designed to withstand a fracture shearing of 50 mm, see Section 5.4.3 and the **Canister production report** for further details. As further discussed in Section 10.4.5, on average between  $9.3 \cdot 10^{-6}$  and  $2.2 \cdot 10^{-5}$  canisters may be sheared 50 mm or more due to earthquakes within the 1,000-year time frame.

## *Status of buffer/backfill after the thermal and saturation phase*

The buffer and, to a lesser extent, the backfill goes through a unique transient thermal and saturation phase in the first few hundred years after deposition. The status of these components after this transient phase is not expected to change much thereafter, meaning that the initial state, in combination with the alterations occurring during the transient phase, to a large degree determine the long-term properties of the buffer and the backfill. Therefore, a specific account of the expected status of the buffer and the backfill after the thermal and saturation phase is given here.

The buffer and the backfill will be deposited as blocks and the gaps between the blocks and the rock are assumed to be filled with bentonite pellets. Water from the rock will enter into the pellets and come into contact with the blocks. The bentonite will take up water and swell. From the time of deposition, the residual heat from the waste will increase the temperature in the near field of the repository. Temperature differences of up to 20 degrees will occur across the buffer for typically 100 years. Elevated temperatures in the near field are expected for about 1,000 years. During this period, the buffer and backfill are expected to evolve as described earlier in this section. The expected final state after the thermal and saturation phase is as set out below.

- After a period of < 100 years to ~6,000 years the buffer is expected to be fully saturated. During the period over which saturation is achieved, the buffer will swell and exert a swelling pressure on the canister, the rock and the backfill. The pressure is too low to have any effect on the canister and rock, but the backfill will deform to a certain extent. This will lead to a small loss of swelling pressure in the top of the deposition holes, but the pressure exerted by the buffer around the canister is expected to remain at its initial value.
- The hydraulic gradients in the unsaturated repository may cause piping and erosion of the buffer and backfill. This may lead to a loss or redistribution of material, but the losses will not jeopardize the function of the buffer nor the backfill.
- The increased temperature in, and the thermal gradient over, the buffer may lead to redistribution of minerals.  $\text{CaCO}_3$  could be enriched close to the canister. The movement of compounds of silica is expected to be negligible.
- The maximum temperature increase and the maximum duration of increased temperature are well below the limits that might cause any significant transformation of the montmorillonite.
- Groundwater from the site will enter into the buffer and mix with the original porewater. This will yield a new composition for the buffer water. Both the composition of the original bentonite and the water from the site are sufficiently well known that the new composition can be estimated.
- At the later part of the initial temperate period, i.e. after 10,000 years, a fraction of a percent of the deposition hole positions may have dilute conditions such that buffer colloids are formed and released. However, given the time it takes for such erosion, no deposition holes will reach advective conditions during the initial temperate period.
- Even if dilute conditions may occur in some of the more transmissive single fractures intersecting a deposition tunnel, at the later part of the initial temperate period, none of them will cause erosion to the extent that this will cause such loss of swelling pressure above deposition holes that these in turn would enter an advective condition. For a few positions where the fracture is connected to a deformation zone, potentially more than 220 tonnes could be lost in a million year perspective, but this is not relevant from the point of view of canister integrity.

In summary, for all identified processes occurring in the buffer and backfill during the saturation and thermal phase the consequences have been estimated. The conclusion is that none of these phenomena will jeopardize the long term performance of the buffer and backfill.

## **Identified uncertainties and their handling in the subsequent analysis**

The main uncertainties in the landscape development during the remaining part of the reference glacial cycle are essentially the same as those dominating during the initial temperate period, i.e. 1) the configuration of the landscape, 2) the timing of different events, and 3) the composition and properties of species and communities inhabiting the future landscape (cf. Section 10.3.3). Even though it is impossible to describe in detail the landscape development during a complete glacial cycle, the systematic landscape analysis and the approach for estimating doses encompasses most of the potential future landscape configurations for the reference glacial cycle.

### **10.4.3 Thermal evolution**

The decreasing temperature and in particular the presence of permafrost and perennially frozen ground may impact the buffer clay, backfill material and copper canister. Primarily it is safety function R4, see Figure 10-2, that may be affected, since it a) states that the temperature in the buffer should  $> -4^{\circ}\text{C}$  in order to avoid buffer freezing and b) that the buffer temperature should be  $> 0^{\circ}\text{C}$  to ensure the validity of the canister shear analysis. Furthermore, there is also a temperature related safety function for retention (BF2c) stating that the backfill temperature  $> -2^{\circ}\text{C}$ , since this is the temperature at which it will freeze. In addition, if the buffer freezes, the pressure exerted on the canister and the rock may increase, an issue requiring separate analyses. Presence of permafrost also affects the hydromechanical conditions (potential for hydraulic jacking) as is further discussed in Section 10.4.4. It is therefore important to analyse i) the depths of permafrost, or more specifically, the depth of perennially frozen ground, ii) the depth of the isotherm corresponding to the temperature criterion used for buffer clay freezing, iii) the depth of the isotherm corresponding to the temperature criterion used for freezing of the backfill material, and iv) the freeze-out of salt that may result in a zone with higher salinity beneath the perennially frozen ground.

#### **Permafrost development**

The depth of permafrost is defined by the depth of the  $0^{\circ}\text{C}$  isotherm, see the **Climate report**, Section 3.4. However, the depth of the perennially frozen ground is often shallower, depending on the prevailing hydrostatic pressure, chemical composition of groundwater and on adsorptive and capillary properties of ground matter. These factors result in the possibility that groundwater water may freeze at temperatures below  $0^{\circ}\text{C}$ , see e.g. the **Climate report**, Section 3.4. The temperature criterion used in SR-Site for buffer freezing is  $-4^{\circ}\text{C}$ , see Section 8.3.2. However, in reality it is likely that buffer clay freezes at even lower temperatures, Section 3.2.2 in the **Buffer, backfill and closure process report**. The criterion used for freezing of the backfill material is  $-2^{\circ}\text{C}$ , see Section 8.4.4.

The prevailing surface conditions, such as air temperature and surface cover, are the main factors governing the spatial and temporal development of permafrost and perennially frozen ground at Forsmark, see the **Climate report**, Section 3.4.4. Subsurface conditions, such as bedrock thermal properties, geothermal heat flow, groundwater salinity and heat produced by the repository, modify the spatial and temporal development, but are of secondary importance compared to surface conditions. For a description of the development of permafrost during the reference glacial cycle, see Section 10.4.1 and the **Climate report**, Section 4.4.3.

#### **Permafrost modelling**

The evolution of permafrost and perennially frozen ground has been investigated by means of numerical modelling in 1D and 2D /SKB 2006c, Hartikainen et al. 2010/. The related mathematical models are based on the theory of mixtures and basic principles of continuum mechanics and thermodynamics considering the freezing ground as an elastic porous medium of soil or rock skeleton saturated by saline groundwater and ice. The models are capable of describing the heat- and mass transfer in a porous medium, freezing of groundwater being affected by groundwater pressure and salt concentration, and freezing-induced groundwater flow (cryogenic-suction). The numerical 2D model also describes the exclusion of salt during freezing and the density dependent groundwater flow in unfrozen and partially frozen ground. The continuum approach is adequate for modelling of permafrost and perennially frozen ground development, since these processes are primarily governed by heat conduction and only secondarily by groundwater flow /Hartikainen et al. 2010/.

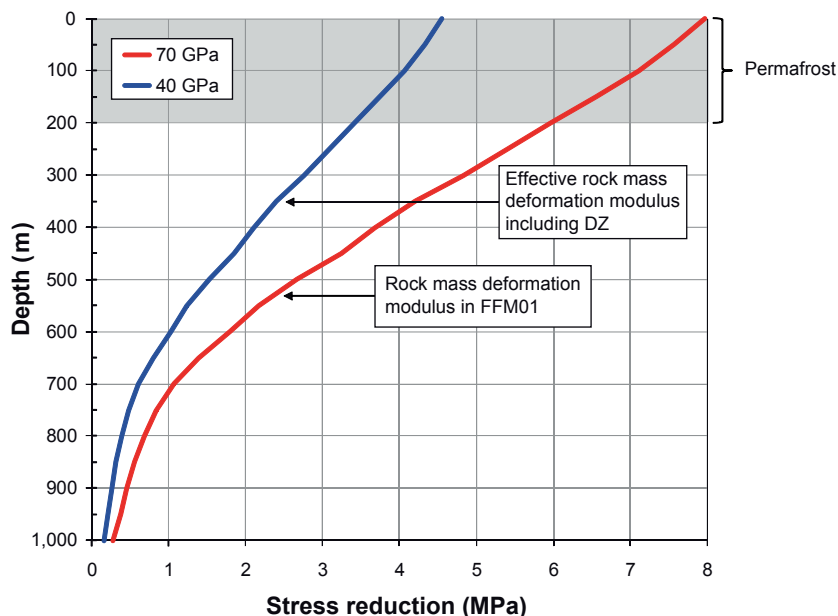


stresses in the rock mass. However, as opposed to the temperate phase the temperature reduction during permafrost conditions affects much larger volumes of the rock mass meaning that thermo-mechanical properties on a larger scale have to be considered, i.e. accounting for surrounding rock with lower stiffness and the presence of deformation zones, which will effectively reduce the deformation modulus of the rock mass. Based on estimates of the rock mass deformation modulus, in the range 40–45 GPa, suggested to be valid for large scale models of the bedrock surrounding the Forsmark site, the results from the present modelling work are scaled to an effective deformation modulus of 40 GPa. Figure 10-111 shows the resulting reduction in horizontal stress as a function of depth. Furthermore, /Hökmark et al. 2010/ make two alternative assumptions regarding the glacially induced pore pressure at different depths.

1. It is assumed to follow the hydrostatic pressure at the ice bed interface, i.e. 98% of the increase in vertical stress due to the glacier, at all times and at all depths. However, as the ice margin is passing over the site or in combination with proglacial permafrost as the ice is advancing, this approach may underestimate the excess pore pressure at large depths.
2. Estimates of the residual pore overpressure as a function of depth as the ice margin is passing over the site are established in 2D using a simplified ice sheet profile /Paterson 1994/ with the suggested ice frontal retreat rate at Forsmark /SKB 2006a/ and with depth-dependent hydraulic properties of the rock mass /Follin et al. 2007b, Vidstrand et al. 2010/. The estimate of the overpressure that could exist under an impermeable proglacial permafrost layer is based on worst case assumptions of the permafrost melting rate, i.e. on a case that maximizes the potential jacking depth under the advancing margin /Lönnqvist and Hökmark 2010/. For the latter pore pressure estimate, the seasonal pressure variations are taken into account.

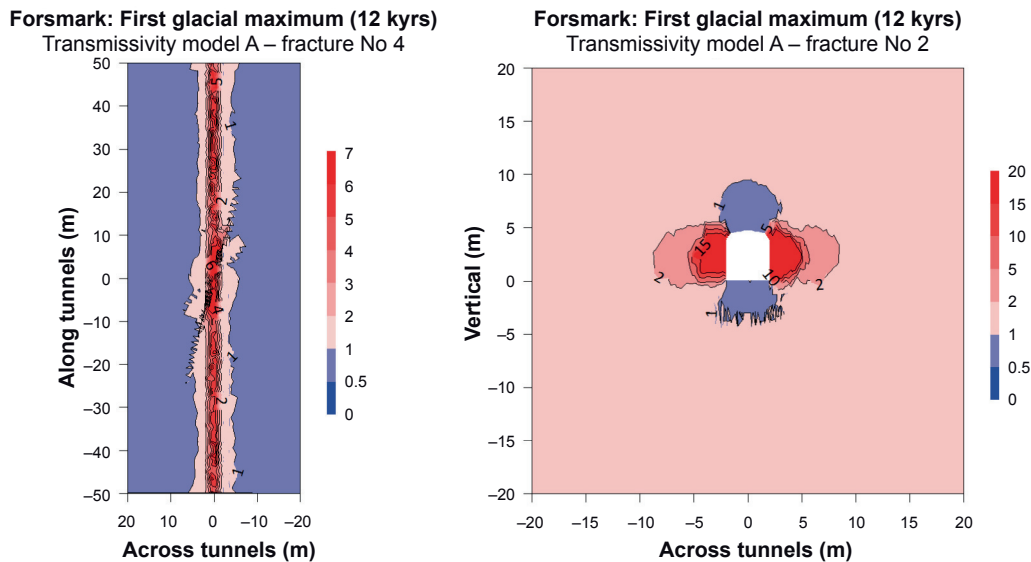
#### Reactivation of fractures during glacial cycle – hydraulic impacts in the far field

Using the modelling approach outlined in Section 10.3.5, /Hökmark et al. 2010/ assess the transmissivity effects for five instances in time, the first glacial maximum (12,000 years after the first mechanical impact due to the ice), ice margin passing over the site in connection with the first episode of ice frontal retreat (after 15,000 years), stress reductions due to forebulge (after 39,000 years), second glacial maximum (after 54,500 years) and ice margin passing over the site in connection with the second episode of ice frontal retreat (58,000 years after the first mechanical impact).



**Figure 10-111.** Horizontal stress reduction (i.e. reduction of compression) during permafrost conditions. The red line is the calculation result based on a local scale rock mass stiffness of 70 GPa. For use in subsequent analyses this stress reduction is revised, shown in the blue line, such that it represent the rock mass stiffness for relevant large-scale elastic properties, i.e. a rock mass stiffness of 40 GPa. From /Hökmark et al. 2010, Figure 7-6/.





**Figure 10-114.** Relative transmissivity change for at the first glacial maximum (after 12 ka) in a fracture (left) parallel to the tunnel floor and (right) a vertical fracture intersecting the tunnel with a small angle projected onto the vertical plane perpendicular to the deposition tunnel. Modified after Figures 8-16 and 8-12 in /Hökmark et al. 2010/.

The present understanding is that the horizontal stress components due to the ice are of the same magnitude or greater than the corresponding vertical stress component and that they exist outside the ice /Lund et al. 2009/. In a reverse stress field ( $\sigma_H > \sigma_h > \sigma_v$ ), which is the case at Forsmark /Glamheden et al. 2007/, this implies that hydraulic jacking is mainly of concern for sub-horizontal fractures.

Possible indications of hydraulic jacking events, in the form of sediment-filled fractures, have been found at Forsmark, to depths of a few tens of metres. However, hydraulic jacking may, in theory, also be initiated at substantially larger depths /Talbot 1999, Hökmark et al. 2006/. Therefore, a special study on the potential for hydraulic jacking during a glacial cycle /Lönngqvist and Hökmark 2010/ has been conducted. It shows that:

- In the absence of proglacial permafrost, hydraulic jacking in front of an advancing ice sheet is unlikely to be initiated at depths greater than about 30 m if the rock can be treated as a continuous and relatively homogeneous porous medium. The possibility that a few highly transmissive fractures in otherwise low permeable rock may transfer high pressures from large distances under the ice to the ice front and thereby cause hydraulic jacking can also be discarded. Analytical estimates indicate that in order to initiate hydraulic jacking at 400 m depth a fracture at least 7.6 km long in otherwise impermeable rock is needed. There are no indications of the existence of such fractures at Forsmark.
- For the case of proglacial permafrost in front of an advancing ice, hydraulic jacking below the permafrost could only be seen for permafrost melting rates much higher than those established for the reference glaciation cycle. Note that the pore pressure beneath the permafrost is completely determined by the pressure at the melting zone, the diffusivity of the rock and the time-frame of the frontal advance, which implies that the initial permafrost thickness will not influence the maximum jacking depth. The worst cases studied had an initial permafrost depth of 200 m with melting rates between 0.5 and 1 m/year and this condition gave maximum jacking depths of around 330–350 m. However, this depth was reduced to about 175–210 m, considering the seasonal variations in the boundary hydrostatic pressure. The reference melting rate resulted in increased pore pressure levels corresponding to jacking depths of less than 10 m. A potential occurrence of open taliks near the repository would further decrease the maximum jacking depth.
- For a retreating ice sheet, the key factors are the frontal retreat rate of the ice and the hydraulic diffusivity of the rock. The maximum jacking depth was established for two assumptions regarding the frontal retreat rate: A much faster frontal retreat rate (500 m/year) suggested by /Talbot 1999/ and the retreat rate of 300 m/year considered to be more relevant for Forsmark /SKB 2006a/. A maximum jacking depth less than 100 m results even for the fastest retreat speed. For the retreat speed relevant for Forsmark (300 m/year) the maximum jacking depth is around 50 m.

bedrock at Lupin consists of an ancient metamorphosed sedimentary rock sequence dominated by quartz feldspar gneiss/phyllite; these were formed some 2.5 Ga, somewhat older than 1.89–1.85 Ga which was the peak of metamorphism at the Forsmark site, characterised by different types of granitoids with subordinate felsic to intermediate volcanic rocks, diorite or gabbro, pegmatite and amphibolite. Whilst the rock types are certainly not identical, they share enough properties to compare qualitatively the general hydrochemical properties at each site. The pH values for sampled groundwaters at Lupin vary between 6 and 9 and bicarbonate concentrations are found to be below  $5 \cdot 10^{-3}$  mol/L. For potassium, the concentrations are higher than for the groundwaters sampled at Forsmark or Laxemar: sub-permafrost groundwaters at Lupin have  $< 2.6 \cdot 10^{-3}$  mol/L. For iron, most of the groundwaters sampled at Lupin had  $< 5.4 \cdot 10^{-5}$  mol/L. Thus, the concentrations and pH values found are not far from those for groundwaters sampled elsewhere, for example at Forsmark, see /Laaksoharju et al. 2008/.

## Evolution of salinity and relevant natural groundwater components

It is estimated that at Forsmark the ground will be frozen to a depth of 50 m or more for around 30 percent of the time in the glacial cycle of the reference evolution, see Figure 10-106. According to these results, the permafrost will not occur over a continuous period of time, but rather thawing will occur between more or less short periods of permafrost, see also the discussion in Section 10.4.1. Some of these permafrost periods will furthermore coincide with the time when the site is covered by an ice sheet.

When water freezes slowly, the solutes present in the water will not be incorporated in the crystal lattice of the ice. During this process, salts that have been present in the surface waters and groundwaters will tend to accumulate at the propagating freeze-out front. This front is, however, not necessarily sharp, because e.g. freezing will take place over a range of temperatures, depending on the salinity, etc. The freezing process can give rise to an accumulation of saline water at the depth to which the perennially frozen front has reached. The saline waters formed in this manner within fractures and fracture zones will sink rapidly due to density gradients.

The calculations made using a two-dimensional model set-up /Hartikainen et al. 2010/ show that when the freezing is extensive (down to several hundred metres depth) a salt front is developed in the calculations. The model also shows that pockets of unfrozen groundwater with high salinity may develop in the perennially frozen rock when the freezing front advances faster than the transport of salt. These results agree qualitatively with the previous generic calculations reported in /Vidstrand et al. 2006/. It should be noted that the model used in /Hartikainen et al. 2010/ does not account for matrix diffusion, and the amounts of salts frozen out in the mobile groundwater are only a fraction of the salt contents in whole rock volume.

The concentration of the frozen out salt has been estimated in these calculations assuming that before the onset of the permafrost the salinity distribution is that found at present in Forsmark. Judging from the results in Figure 10-39, Section 10.3.7, it may be that these initial salinities are overestimated, as the groundwaters will become gradually more dilute before the start of the permafrost.

Nevertheless the results of the 2D modelling /Hartikainen et al. 2010/ indicate only a very moderate increase in salinities around the repository volume, not exceeding 1%, for the most extreme permafrost simulation, that is, for the dry variant of the repetition of the last glacial cycle with an air temperature decreased by 8 degrees. That is, even for the most extreme permafrost extent simulated, the calculated groundwater salinities in the repository volume do not exceed those found at present.

The possibility of upconing of deep saline groundwater to repository depths during permafrost conditions was addressed in /King-Clayton et al. 1997/. This may possibly occur in the vicinity of permanent discharge features such as some taliks. Such discharge features mainly occur along more extensive conductive deformation zones. In Forsmark, where the topography is quite flat, the probable location of taliks is at some distance from the candidate repository area, as estimated from the landscape development following the reference evolution shore-level displacement at Forsmark, see the **Climate report**, Section 4.5.2.

When the permafrost melts and decays there will be a release of dilute melt water from the upper highly permeable network of fractures. At this stage the low permeability matrix which has preserved (or accumulated) its salinity, especially at greater depths, will probably be more saline than

Based on observations and results from pessimistic modelling, oxygen intrusion to repository depth in highly transmissive deformation zones during the advance or retreat of an ice sheet cannot be discarded. However, model results indicate that hundreds of years of the worst glacial situation, a situation which does not occur in the reference evolution, would be needed for oxygen to reach only a few of the canister positions in the repository. Therefore it is concluded that reducing conditions will prevail in the deposition holes of the repository, satisfying the safety function indicator criterion R1a in Figure 10-2.

#### 10.4.8 Effects on buffer and backfill

##### **Freezing**

As concluded in Section 10.4.3, temperatures leading to buffer and backfill freezing do not occur in the reference evolution. Freezing of the upper parts of access tunnels or sealed boreholes could, however, not be excluded. Nevertheless, this section addresses the conditions when freezing may occur and how this affects the clay barriers. This information is then used in Section 12.3 when assessing consequences of more extreme future climates.

##### **General**

At temperatures below 0°C it can be anticipated that the water in the buffer and the backfill would turn into ice. This is not an issue for the materials themselves since the process is reversible and they will regain their properties after thawing /Birgersson et al. 2010/. However, the formation of ice could lead to

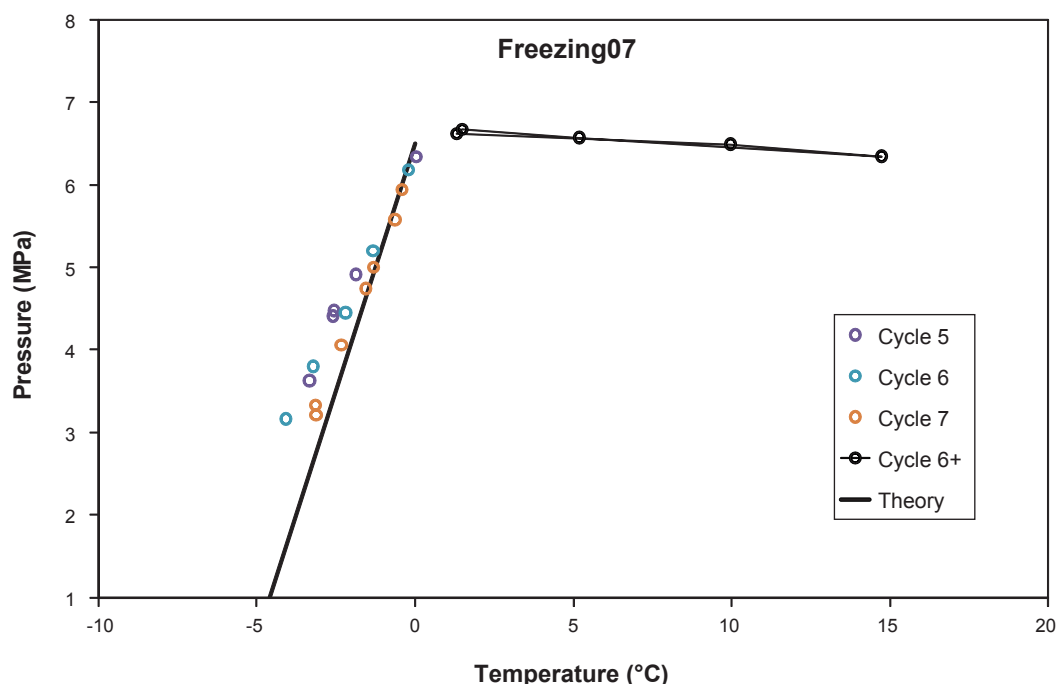
1. An increased pressure on the canister and rock.
2. Redistribution of material due to ice lens formation.

/Birgersson et al. 2010/ have investigated the behaviour of compacted bentonite below 0°C. It was investigated how swelling pressure (i.e. sealing properties) change with temperature and under what conditions bentonite freezes. The freezing point of a soil sample is defined as the temperature at which ice starts to form in the material. When ice formation occurs in confined bentonite a substantial pressure increase is expected due to volume expansion of water. Bentonite is a swelling material, which makes it rather unique as a soil in the sense that some of its properties are dependent on external conditions. The process of swelling, specifically, only occurs when bentonite is in contact with an external aqueous reservoir, and the concept of swelling pressure can consequently only be defined under such conditions. This means, in particular, that a bentonite component within the KBS-3 repository will be affected by freezing as soon as the groundwater in the surrounding rock freezes even though the component itself may remain unfrozen. The process of freezing bentonite in the following context therefore also includes the temperature range between the freezing point of the aqueous reservoir and the actual freezing point of the bentonite soil, in order to provide a full description of bentonite characteristics as the temperature is lowered.

There is a critical temperature below 0°C, here denoted  $T_c$  and measured in °C, at which swelling pressure is completely lost.  $T_c$  depends only on swelling pressure measured at 0°C, and not explicitly on clay specific quantities like montmorillonite content, montmorillonite layer charge or density.

/Birgersson et al. 2010/ have provided a theoretical description of the pressure response due to temperature in bentonite above  $T_c$ . From these results it can be concluded that any bentonite component of the KBS-3 repository – buffer, backfill or borehole seals – will strive to lower its pressure as the temperature drops below 0°C. The size of the equilibrium pressure drop depends, for all relevant bentonite densities, basically only on the difference in molar entropy between bulk water and ice, which at 0°C corresponds to 1.2 MPa/°C. Because the pressure drop is determined by properties not related to the clay, the same behaviour is expected independent of what specific bentonite is used. The dominating parameter that determines  $T_c$  is thus the equilibrium swelling pressure at 0°C (which of course in turn is determined by e.g. density, montmorillonite content, montmorillonite layer charge etc).

Figure 10-155 shows pressures evaluated for samples of the Ibeco RWC (Dep Can) bentonite for temperatures both below and above 0°C.



**Figure 10-155.** Equilibrium pressure vs. temperature for Dep-Can (Ibeco RWC) bentonite at a swelling pressure above 0°C of ~7 MPa /Birgersson et al. 2010/. The freezing point ( $T_c$ ) of the sample is below -8°C. The line labelled “Theory” shows the expected pressure response if the water saturated bentonite is treated thermodynamically equivalent to a salt solution. /Birgersson et al. 2010/.

Confined bentonite in contact with saline ground water results in a lower swelling pressure above 0°C as compared to non-saline conditions. This effect, however, does not result in an increased freezing temperature as the freezing point of the external aqueous reservoir lowers. Actually, saline conditions lead to a lower freezing point of bentonite because salt enters the clay and contributes to lowering the chemical potential of the water. Therefore, only non-saline conditions need to be considered.

### Buffer

The buffer materials in SR-Site are MX-80 and Ibeco RWC bentonites that have a mean bulk density of 2,000 kg/m<sup>3</sup>, see Section 5.5. The corresponding swelling pressure of these materials under non-saline conditions is 7–8 MPa, which, in turn, corresponds to a  $T_c$  of approximately -6°C. Considering also the accepted density range of 1,950–2,050 kg/m<sup>3</sup>, which gives a swelling pressure interval of 5–13 MPa /Karlund 2010/, the range for  $T_c$  is between -4°C and -11°C.

### Backfill

The swelling pressure of the backfill can be significantly lower than that in the buffer. The swelling pressure of the “initial state” backfill defined in Chapter 5 is ~3 MPa, which would give a critical temperature of -2.5°C. However, this represents the average swelling pressure and as described in Section 10.3.9 there will be remaining density gradients within the backfill. The minimum density in the backfill will be 1,370 kg/m<sup>3</sup>, which corresponds to a swelling pressure of ~1 MPa according to Figure 5-19. This would give a  $T_c$  of -0.8°C for the loosest sections of the backfill in the deposition tunnel. Furthermore, the repository closure, which, in accordance with the reference design, is similar to the backfill in deposition tunnels, is extended vertically in ramp and shafts and therefore parts of it will experience temperatures lower than those at repository level. Freezing of the backfill is not a problem per se, as the process has been demonstrated to be reversible. However, it can be imagined that freezing could occur in the backfill in a position closer to the surface when the rock surrounding the repository is frozen. This could lead to increased pressures in the repository as liquid water is “trapped” in a frozen rock matrix. Such a scenario can only occur, however, when the temperature at repository level is below 0°C.

Darcy flux. Positions with the highest fluxes are also with high likelihood among the two percent of positions exposed to dilute groundwaters. Since the 23 positions are much less than the two percent of the 6,000 positions assumed to be exposed to dilute water, further efforts to reduce the estimate of two percent being exposed to dilute groundwater would not readily yield any further reduction in the number of advective positions.

Also, assuming dilute conditions in **all** deposition holes **throughout the glacial cycle**, then 7 deposition holes are calculated to reach advective conditions in 120,000 years assuming temperate flow conditions and 4 deposition holes if the appropriate time averaged flow conditions (the mean value of  $q^{0.41}$ , Figure 10-147), is assumed. Therefore, it is concluded that less than one in a thousand of the 6,000 deposition holes are expected to exhibit advective conditions during the first glacial cycle.

As also found in Section 10.3.11 none of the tunnel intersecting single fractures will cause erosion of the backfill to the extent that it loses so much swelling pressure that advective conditions must be assumed in underlying deposition holes. For a few positions where the tunnel is intersected by a deformation zone, potentially more than 220 tonnes could be lost, but this is not relevant from the point of view of canister integrity since no deposition holes will be located there.

In conclusion, the quantitative evaluations of the erosion process indicate that substantial losses, affecting several of the buffer safety functions negatively, are expected to occur in less than one in a thousand of the deposition holes during the first 120,000-year glacial cycle, whereas, in a million year perspective, 23 deposition positions, i.e. less than one percent, are calculated to reach advective conditions assuming exposure to dilute groundwater 25 percent of the time. The buffer erosion calculations are integrated with the calculations of canister corrosion in a million year perspective, see Section 10.4.9, and, in the case of resulting canister failures, to calculations of radionuclide transport in Chapter 13.

### ***Liquefaction***

Liquefaction, as observed in loose clay and sand, cannot take place in a bentonite with high density, since the effective stress that holds the clay together is high due to the swelling pressure. Furthermore, the **Buffer, backfill and closure process report**, Section 3.4.2, conclusively rules out that a very high hydrostatic pressure during a reference glacial event could reduce the effective stress (swelling pressure) of the buffer to zero. Pressure increases resulting from earthquakes have been demonstrated as not being able to cause liquefaction in the buffer, see the **Buffer, backfill and closure process report**, Section 3.4.2.

### ***Effects of saline water on buffer and backfill***

Hydraulic conductivity and swelling pressure of the buffer and backfill, as affected by different groundwater salinities are presented in Section 10.3.9. The conclusion is that the hydraulic properties of the buffer will not be significantly affected by the intrusion of saline water. The conclusions in that section are valid at chloride concentrations of up to 3 M (17.5% NaCl). The highest expected value at Forsmark is a salinity of TDS = 20 g/L, i.e. about 2 percent, as a consequence of the upconing of deep saline waters when the ice front margin is located on top of the repository, see Section 10.4.7.

### ***Mechanical effects of increased flow***

For the case where there are strong hydraulic gradients in a fracture intersecting a deposition hole, it could be imagined that buffer could be lost by shearing of particles from the bentonite gel by seeping water. For physical shearing the cohesiveness of the gel has to be overcome by the friction force on the gel. The yield stress of the gel and the shear stress of the water will determine when this mechanism is active. The non-Newtonian properties, especially the Bingham yield stress must be quantified. Neretnieks et al. 2009/ presents a model for the shear stress as a function of the hydraulic gradient and fracture aperture. Figure 10-157 shows the shear stress as a function of the hydraulic gradient based on the output from hydrogeological modelling of the glacial Base case in SR-Site, see Table 10-25 in Section 10.4.6, and aperture.



### **Buffer safety functions**

For the initial temperate period, it was concluded that the saturated buffer density in deposition holes where piping does not occur will be in the interval allowed for the initial state, ie. 1,950–2,050 kg/m<sup>3</sup> around the canister.

Up to 2 percent of deposition hole positions may experience dilute conditions during a glacial cycle, although only for a limited part of the time. Assuming that these positions coincide with the positions of the highest flow, only one out of 6,000 deposition holes is calculated to also lose buffer mass to the extent that advective conditions must be assumed during the 120,000 year reference glacial cycle.

#### **Buff1. Limit advective transport**

a) Hydraulic conductivity  $< 10^{-12}$  m/s

For deposition holes within the initially allowed buffer density range, the hydraulic conductivity criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see Section 10.4.8. For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

b) Swelling pressure  $> 1$  MPa.

For deposition holes within the initially allowed buffer density range, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see Section 10.4.8. For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

#### **Buff2. Reduce microbial activity**

For this safety function to be fulfilled it is required that the buffer density is high.

For deposition holes within the initially allowed buffer density range, this safety function is fulfilled.

For a deposition hole that has experienced substantial loss of buffer mass due to erosion/colloid release, this safety function can, however, not be guaranteed.

#### **Buff3. Damp rock shear**

For this safety function to be fulfilled, it is required that the saturated buffer density is less than 2,050 kg/m<sup>3</sup>. 2,050 kg/m<sup>3</sup> is the upper allowed bound of the initial density and as no relevant processes that would increase the buffer density have been identified, it is concluded that this safety function is fulfilled for all deposition holes.

#### **Buff4. Resist transformation**

For this safety function to be fulfilled, it is required that the buffer temperature is less than 100°C. The peak buffer temperature will occur a few tens of years after deposition. At the start of the reference glacial cycle (10,000 years after deposition), the buffer temperature will be similar to that of the ambient, natural rock temperature. There is thus no conceivable way in which the buffer temperature could exceed 100°C during the reference glacial cycle.

#### **Buff5. Prevent canister sinking**

For this safety function to be fulfilled, it is required that the buffer swelling pressure exceeds 0.2 MPa. For deposition holes within the initially allowed buffer density range, the swelling pressure criterion is fulfilled with ample margin, see above. For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function cannot be guaranteed. However, if advective conditions prevail, the fact that the canister sinks is of secondary importance.



## **Buff6. Limit pressure on canister and rock**

a) Swelling pressure < 15 MPa

Since no process is identified where the buffer material will be added during the next glacial cycle, this maximum swelling pressure criterion will be upheld.

b) Temperature > -4°C.

As mentioned regarding the rock safety function R4 above, the criterion is expected to be fulfilled with ample margin for the reference glacial cycle.

## **Backfill safety functions**

### **BF1. Counteract buffer expansion**

For this safety function to be fulfilled it is required that the density of the backfill material is sufficiently high. As shown in Section 10.2.4, the largest possible erosion due to piping will be 1,640 kg. Erosion in the backfill will basically mean that material is redistributed within the tunnel itself. Considering the large mass of backfill in the tunnel a redistribution of 1,640 kg can be assumed to have no impact at all on the backfill performance.

Even if dilute conditions occur in some of the more transmissive single fractures intersecting deposition tunnel, during the next glacial cycle, none of them will cause erosion to the extent that this will result in such loss of swelling pressure above deposition holes that these in turn would enter an advective condition. For a few positions where the fracture is connected to a deformation zone, potentially more than 220 tonnes could be lost, but this is not relevant from the point of view of canister integrity.

## **Canister safety functions**

### **Can1. Provide corrosion barrier**

The only reason for canister failure due to corrosion during the remaining part of the glacial cycle is by corrosion for advective conditions in the deposition holes, caused by erosion of the buffer when exposed to dilute groundwaters. Up to around one canister may fail over the entire 10<sup>6</sup> year assessment period for this reason. The results from the erosion/corrosion calculations are further transferred to the radionuclide transport calculations, giving the time needed for erosion and corrosion specifically for each deposition hole and for each sulphide concentration.

### **Can2. Withstand isostatic load**

For this safety function to be fulfilled, it is required that the canister withstands isostatic loads above 45 MPa. The fulfilment of this safety function is assured by the design of the canister, see Section 5.4.3 and the **Canister production report**. It may also be noted that the maximum expected isostatic load on the canister at the Forsmark site is 4.5 MPa hydrostatic pressure, up to 13 MPa isostatic swelling pressure from the bentonite and a maximum additional 26 MPa hydrostatic pressure from a future ice sheet in the Weichselian reference evolution. The maximum total isostatic pressure to which the canister will be subjected can thus be estimated to be 43.5 MPa.

The probability for local canister insert damage at 44 MPa over-pressure is vanishingly small, as demonstrated by probabilistic calculations, see Section 5.4.3. Furthermore, the criterion for failure is that a global collapse occurs, which is not expected for pressures below 100 MPa, see further Section 5.4.3. As a consequence, no canister failures are expected at the maximum over-pressure that could be experienced at the Forsmark site in the reference evolution.

### **Can3. Withstand shear loads**

Canister failures due to future earthquakes are avoided through the use of respect distances and acceptance criteria for deposition holes, adapted to the ability of the canister to resist loads from fracture shear movements. However, it cannot be fully ruled out that such failures will occur, see discussion of rock safety function R3b for estimates of the likelihood of such failures.

## 10.5.1 Safety functions at the end of the assessment period

The following is an account of all safety functions in Figure 10-2 at the end of the one million year assessment time, often as a comparison to the situation after the initial glacial cycle reported in Section 10.4.11.

### Rock safety functions

#### R1. Provide chemically favourable conditions

##### a) Reducing conditions; Eh limited

No challenges to the conclusion for the initial glacial cycle, that reducing conditions will prevail, have been identified. It is, therefore, concluded that reducing conditions will prevail throughout the assessment period.

##### b) Salinity; TDS limited.

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that salinity levels will remain limited.

##### c) Ionic strength; $\Sigma q[M^{q+}] > 4$ mM charge equivalent.

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that additional periods of temperate and glacial conditions where this safety function indicator is not fulfilled must be assumed.

##### d) Concentrations of $HS^-$ , $H_2$ , $CH_4$ organic C, $K^+$ and Fe; limited.

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that concentrations of K and Fe will remain limited and that sulphide concentrations are expected to be  $\leq 10^{-5}$  mol/L for most deposition positions averaged over the time period.

##### e) pH; pH < 11.

Repetitions of the same pattern of natural variations as for the initial glacial cycle are expected, meaning that pH is not expected to exceed 10. Possibly, continued releases of leach water from grout, shotcrete and cement may exhibit pH-values of around 9 even after the initial glacial cycle.

##### f) Avoid chloride assisted corrosion; pH > 4 and $[Cl^-] < 2$ M.

Repetitions of the same pattern of natural variations as for the initial glacial cycle are expected, which means that these safety function indicator criteria are fulfilled throughout the period.

#### R2. Provide favourable hydrologic and transport conditions

##### a) Transport resistance in fractures, $F$ ; high

Repetitions of the same pattern of variations of gradients and small alterations of fracture transmissivity for different glacial loads as for the initial glacial cycle are expected. This means that the variation in groundwater flow and thus in transport resistance of the initial glacial cycle will also be applicable for the subsequent glacial cycles.

##### b) Equivalent flow rate in buffer/rock interface, $Q_{eq}$ ; low.

Repetitions of the same pattern of variations of gradients and small alterations of fracture transmissivity for different glacial loads as for the initial glacial cycle are expected. This means that the variation in groundwater flow and thus in equivalent flow rate of the initial glacial cycle will also be applicable for the subsequent glacial cycles. However, in deposition holes where advective conditions need to be assumed,  $Q_{eq}$  should be replaced by the flow in the fracture intersecting the deposition hole, as further discussed in Section 10.4.9.

#### R3. Provide mechanically stable conditions

##### a) GW pressure; limited.

Repetitions of the same pattern of variations as for the initial glacial cycle are expected, meaning that increased pressures will occur for glacial conditions. As for the initial glacial cycle, this yields maximum total groundwater pressures of around 30 MPa.

b) Shear movements at deposition holes  $< 0.05$  m.

For the 1,000,000-year time frame, using the most pessimistic way of accounting for the combined effects of multiple earthquakes, between  $8.1 \cdot 10^{-3}$  and  $6.9 \cdot 10^{-2}$  canisters may be sheared 50 mm or more.

c) Shear velocity at deposition holes  $< 1$  m/s.

As for the initial glacial cycle it is shown that shear velocities will stay below the 1 m/s limit.

#### **R4. Provide thermally favourable conditions**

Repetitions of the same pattern of variations as for the initial glacial cycle are envisaged. For the first glacial cycle it was shown that the  $-4^{\circ}\text{C}$  isotherm reaches a maximum depth of  $\sim 150$  m and if also considering a quite unrealistic and most extreme combination of uncertainties, the uncertainty range for the perennially frozen ground reach a maximum depth of  $\sim 420$  m and at the same time, the uncertainty range for the  $-4^{\circ}\text{C}$  isotherm reach a maximum depth of  $\sim 320$  m. These results conclusively show that the  $-4^{\circ}\text{C}$  isotherm does not reach repository depth in the reference glacial cycle and since the uncertainty interval for the perennially frozen ground does not reach 450 m depth, even in this most extreme combination of all uncertainties, freezing of groundwater at repository depth is excluded in the reference glacial cycle. In this most extreme situation, the lowest temperatures at the 450 and 470 m depths are approximately  $-0.5^{\circ}\text{C}$  and  $0^{\circ}\text{C}$ , respectively. For periods with glacial conditions, the ice sheet acts to insulate the bedrock from the low air temperatures, meaning that permafrost depths are smaller than for periglacial conditions.

a) Temperature  $> -4^{\circ}\text{C}$  (avoid buffer freezing).

This safety function is fulfilled, even considering that the maximum permafrost depths for the reference glacial cycle may increase by up to 37 m, see the **Climate report**, Section 4.5.3, when the residual power from the fuel does not counteract the development of permafrost after the initial glacial cycle.

b) Temperature  $> 0^{\circ}\text{C}$  (validity of can shear analysis).

When not considering the uncertainties related to permafrost growth, the bedrock temperature is well above  $0^{\circ}\text{C}$  during the first and all following safety assessment period glacial cycles. In the case of the most extreme, and quite unrealistic, combination of uncertainties related to permafrost growth, the bedrock temperature at repository level may have a temperature marginally below  $0^{\circ}\text{C}$ . However, since this case is considered unrealistic it is anyway judged that the safety function is upheld for the entire assessment period of 1 million years.

#### **Buffer safety functions**

As for the initial glacial cycle, quantitative evaluations of the buffer erosion process indicate that substantial losses, affecting several of the buffer safety functions negatively, cannot be ruled out, potentially for a fraction of the deposition holes during the one million year assessment period. These potential losses would be higher than for the initial glacial cycle.

This influences the evaluation of several of the buffer safety function indicators, as discussed below.

#### **Buff1. Limit advective transport**

a) Hydraulic conductivity  $< 10^{-12}$  m/s.

For deposition holes within the accepted range of buffer density, the hydraulic conductivity criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see Section 10.4.8. For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

b) Swelling pressure  $> 1$  MPa.

For deposition holes within the accepted range of buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle, see Section 10.4.8. For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function can, however, not be guaranteed.

### **Buff2. Reduce microbial activity**

For this safety function to be fulfilled it is required that the buffer density is high.

For deposition holes within the accepted range of buffer density, this safety function is fulfilled.

For a deposition hole that has experienced substantial loss of buffer mass due to erosion/colloid release, this safety function can, however, not be guaranteed.

### **Buff3. Damp rock shear**

For this safety function to be fulfilled, it is required that the saturated buffer density is less than 2,050 kg/m<sup>3</sup>. Since 2,050 kg/m<sup>3</sup> is the upper bound of the accepted initial state and as no relevant processes that would increase the buffer density have been identified, it is concluded that this safety function is fulfilled for all deposition holes.

### **Buff4. Resist transformation**

For this safety function to be fulfilled, it is required that the buffer temperature is less than 100°C. As for the initial glacial cycle, there is no conceivable way in which the buffer temperature could exceed 100°C during the assessment period.

### **Buff5. Prevent canister sinking**

For this safety function to be fulfilled, it is required that the buffer swelling pressure exceeds 0.2 MPa.

For deposition holes within the acceptable buffer density range, the swelling pressure criterion is fulfilled with ample margin, see above.

For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, this safety function cannot be guaranteed. However, if advective conditions prevail, the fact that the canister sinks is of secondary importance.

### **Buff6. Limit pressure on canister and rock**

a) Swelling pressure < 15 MPa.

Since no process is identified where buffer material will be added during the future glacial cycles, this maximum swelling pressure criterion will be fulfilled.

b) Temperature > -4°.

As mentioned regarding the rock safety function R4, the criterion is expected to be fulfilled with ample margin.

## ***Backfill safety functions***

### **BF1. Counteract buffer expansion**

Even though dilute conditions may occur in some of the more transmissive single fractures intersecting deposition tunnels, during the 10<sup>6</sup> years assessment period, none of them will cause erosion to the extent that this will result in such loss of swelling pressure above deposition holes that these in turn would enter an advective condition. For a few positions where the fracture is connected to a deformation zone, potentially more than 220 tonnes could be lost, but this is not relevant from the point of view of canister integrity.

## ***Canister safety functions***

### **Can1. Provide corrosion barrier**

The only reason for canister failure due to corrosion during future glacial cycles is by corrosion for advective conditions in the deposition holes, caused by erosion of the buffer when exposed to dilute groundwaters. On average less than one canister may fail over the entire 10<sup>6</sup> year assessment period for this reason. The results from the erosion/corrosion calculations are further transferred to

the radionuclide transport calculations, giving the time needed for erosion and corrosion specifically for each deposition hole and for each sulphide concentration.

## Can2. Withstand isostatic load

Since repetitions of the maximum loads experienced during the initial glacial cycle are expected for the remainder of the assessment period, it is concluded that this safety function will be upheld also for the one million year assessment time.

## Can3. Withstand shear loads

Canister failures due to future earthquakes are avoided through the use of respect distances and acceptance criteria for deposition holes, adapted to the ability of the canister to resist loads due to fracture shear movements. However, it cannot be fully ruled out that such failures will occur, see discussion of geosphere safety function R3b for estimates of likelihoods of such failures.

## Conclusions for consequence calculations

The following conclusions for radionuclide transport can be drawn.

- One cause for canister failure that has not been ruled out for the one million year assessment period is an earthquake caused by changes in the glacial load. The likelihood of this type of failure is low, even when the entire assessment period is considered.
- Failure due to corrosion for advective conditions in a partially eroded buffer must be also considered for the one million year assessment time. On average less than one canister may fail due to this cause.
- All other conclusions regarding consequence calculations drawn for the initial glacial cycle, see Section 10.4.11, are also considered to be valid for repeated cycles.

## 10.6 Global warming variant

### 10.6.1 External conditions

There is a large range of potential future climate developments when the combined effect of natural and anthropogenic climate change is considered. One such case is described in the present *Global warming variant*. This variant describes a future climate development influenced by both natural climate variability and climate change induced by anthropogenic emissions of greenhouse gases, with the latter resulting in weak to moderate global warming. In order to cover a reasonably broad array of future climate developments based on present knowledge, a case of *Extended global warming* is also included in the SR-Site safety assessment, describing a situation with stronger and longer-lasting global warming.

In SR-Site, there are two main reasons for analysing cases of climates warmer than the reference glacial cycle; i) modelling studies of the climate response to increased greenhouse gas emissions, mainly CO<sub>2</sub>, indicate that global temperatures will increase in the future under such conditions, e.g. /IPCC 2007, Kjellström et al. 2009a/, and ii) natural long-term climate cycles are believed to be driven mainly by changes in solar insolation, see the **Climate report**, Section 2.2, and the coming 100,000 year period is initially characterised by exceptionally small amplitudes of insolation variations /Berger 1978/, suggesting that the present interglacial may be exceptionally long. By considering the known future changes in insolation, /Loutre and Berger 2000/ and /Berger and Loutre 2002/ suggest that the interglacial may end ~50,000 years after present. Given this insolation forcing, the results suggest that a growth of the Greenland-, Eurasian- and North American ice sheets would not start until after 50,000 years after present even without increased CO<sub>2</sub> levels. The global warming variant handles these future variations in insolation, as well as the effect of low to moderate global warming from an anthropogenic increase of atmospheric CO<sub>2</sub> levels.



the infiltration of these waters were relatively large. In fact the influence of the last Littorina Sea is evident at Forsmark at shallower depths, above ~300 m, and south-east of the candidate repository area where the higher overall rock hydraulic conductivity has allowed the infiltration of these marine waters driven by density gradients. Nevertheless, as mentioned in Section 10.3.7, when considering the impact of the most extreme pathways from the surface to the repository in the hydrogeological simulations depicted in Figure 10-32, it cannot be excluded that a fraction of the deposition holes may experience dilute conditions during this long temperate period. As shown in the figure, approximately 2 percent of deposition hole locations experiences dilute conditions after the 60,000 years of temperate conditions assumed within the Global warming variant. Considering temperate conditions over the entire 1,000,000 years this fraction would still lie well below 10 percent.

The conclusions are, therefore, similar to those presented in Sections 10.3.7 and 10.4.7. For the whole first temperate period following repository closure, anoxic groundwater conditions will prevail at repository depth, in spite of the increasing proportion of meteoric waters with time, thus satisfying the criterion for the safety function indicator R1a in Figure 10-2. Salinities during this period will be limited, ensuring that the swelling properties of the buffer and backfill are not negatively affected, cf. the safety function indicator R1b in Figure 10-2. Cation concentrations, expressed as charge,  $\sum q[M^{q+}]$ , will be in general well above 0.004 mol/L in the candidate repository volume, although it cannot be excluded that for a fraction of deposition holes the cation concentrations will be below the limit where montmorillonite colloids start to become stable.

The concentration of sulphide, which is another important parameter, is expected to remain at the levels found in the Forsmark groundwaters at present. For colloids, concentrations are also expected to remain at the levels that have been measured during the site investigations, i.e. less than 200 µg/L /Hallbeck and Pedersen 2008/.

## **Buffer and deposition tunnel backfill**

The buffer and deposition tunnel backfill will not be significantly affected by the different evolution in the global warming variant. The main difference is that the temperate period will be longer and glacial conditions will occur later, which will have an effect on the groundwater chemistry, etc. However, as shown in Section 10.3.11, even if “dilute” conditions persist all the time, still less than 7 percent of the deposition holes will reach advective conditions in a million year perspective.

## **Canister**

An initial 100,000 year long warm period will have negligible impact on canister performance. The prolonged period before the first occurrence of permafrost is expected to lead to a longer period of exposure to groundwaters of meteoric origin, with some influence at repository depth, but the groundwater conditions will be similar to those of the reference evolution. The concentration of sulphide is expected to remain at the levels found in the Forsmark groundwaters at present.

The canister corrosion analyses presented in Section 10.4.9, for canister failure due to a partially eroded buffer also covers these cases. A somewhat longer period of dilute conditions in the first glacial cycle, than the 25% of the time in the reference evolution, has a very minor effect on the average number of failed canisters. This is further elaborated in the sensitivity analyses in Section 12.6.2.

The reduced ice-sheet thickness will lead to a lower mechanical load on the canister during the first glacial cycle. This may also lead to a lowering of the risk for the occurrence of larger earthquakes, but as discussed in Section 10.4.5 it is not trivial to adapt the earthquake frequency estimates to the occurrence of glaciations. This means that the earthquake probability, and the potential shearing of canisters, is cautiously assumed to be the same for the global warming variant, as for the reference glacial cycle.

## **10.6.4 Safety function indicators for the global warming variant**

Based on the contents of Section 10.6.3, the status of the safety function indicators at the end of a prolonged period of temperate climate can be expected to be very similar to those reported for the initial temperate period in Section 10.3.16. Therefore, no detailed account of the safety function indicators is given here.