Strål
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Technical Note

2014:39

"Wormhole" and Multiple Loss of Buffer Safety Function Scenarios

Main Review Phase

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Syftet med detta projekt är att utforska verkliga och/eller hypotetiska korrosionsfall i slutförvarsmiljön med betoning på konsekvenser för kapselns livslängd. En avgränsning är att endast korrosionsmekanismer som kan hanteras med materialbalansöverväganden är inkluderade (dvs. korrosionsmekanismer som är relaterade till mekaniska laster som spänningskorrosion ingår inte). I detta avrop bör ingå grundvattenflöde och kemiska betingelser som påverkar kapselkorrosion, varianter av bufferterosion och dess påverkan på kapselkorrosion, samt varierande korrosionsmekanismer samt geokemiska förutsättningar.

Författarnas sammanfattning

Under SSM:s workshop om utveckling av kapselkorrosion diskuterades maskhålsfallet baserat på FEP Bu07 om kanalbildningserosion av bentonitbufferten. Den efterföljande analysen fann att penetrationstiden för kopparkapseln utifrån hypotetisk storlek och placering av maskhålet är kortare än tidigare förutspått. Observera att korrosionsanalysen gjordes genom att förutsätta att ett maskhål kan bildas. Ingen analys har visat att maskhålet kan uppkomma och förbli stabilt. SKB:s undersökning visade att bildning av maskhål är omöjligt för en intakt buffert efter att bufferten blivit helt mättad. I "maskhål"-scenariot, är bildningen av ett rör baserat på antagandet att en lokalt hög gradient av grundvatten kan bidra till kanalbildning.

Denna tekniska rapport analyserar miljömässiga förutsättningar som påverkar den potentiella bildningen, stabiliteten och uthålligheten av lokala bufferterosionsfenomen för att undersöka maskhål frågan. Fokus ligger på den höga hydrauliska gradienten och därmed koncentrerade flöden i deponeringshålet. För detta ändamål togs en enkel modell fram för att erhålla den kritiska hydrauliska gradienten för ett givet intervall av buffertsvälltryck. Den kritiska hydrauliska gradienten är definierad som den lägsta gradienten som krävs för att hålla ett rör öppet. Den beräknade kritiska hydrauliska gradienten varierar från 8,2 - 8800 vilket är tiopotenser högre än 10^{-6} - 1.0, den modellerade omgivande hydrauliska gradienten. Detta intervall är också i allmänhet högre än den omgivande hydrauliska gradienten under istiderna, som sträcker sig från 0,15 till 1,49. Det lägsta värdet: 8,2, vilket motsvarar en delvis eroderad buffert, är fortfarande större än den högsta glaciala gradienten. Det är därför högst osannolikt att bilda ett maskhål över en intakt bentonitbuffert grund av en hög hydraulisk gradient.

En fråga som är relaterad till ”maskhål”-bildning och -stabilitet är flödet i sprickor som skär deponeringshålen. Man kan spekulera om en alternativ flödesmodell, s.k. gles kanalnätverksmodell (SCN), skulle medföra betydligt högre flöde in i en bråkdel av deponeringshålet än den diskreta nätverksmodellen (DFN) modell som användes i SKB SR-Site säkerhetsanalys. Följaktligen skulle dessa deponeringshål vara mer benägna att bilda ”maskhål” genom bufferten. SCN-modellen beaktades därför att modelleringsresultaten visade sig passa fältobservationer bättre än DFN-modellen. By evaluating the SCN model and results, it was found that there is no sufficient evidence to support the speculation. Genom att utvärdera SCN-modellen och medföljande resultat visade det sig att det inte finns tillräckliga bevis för att stödja denna spekulation. Den främsta orsaken är kopplad till modellantaganden. I SCN-modellen antas ett horisontellt, öppet, cylindriskt hål med noll huvud och föremål för ett konstant randvillkor på ett radiellt avstånd av 45-meter från centrum av kaviteten. Den resulterande hydrauliska gradienten är omkring 4,5 i den radiella riktningen in mot centrum, vilket inte är tillståndet efter förslutning hos förvaret när buffertarna blivit mättade och omgivningens hydrauliska gradient har återupptagits.

Den sista frågan angående ”vad händer om” scenarier för kapselkorrosion avser det fall som bygger på att samtidiga förluster av två eller flera buffertsäkerhetsfunktioner är möjliga. Den främsta drivkraften för dessa scenarier antas vara en förlust av buffertdensiteten orsakad av kemisk, dvs. kolloidrelaterad erosion. I SKB:s buffertadvektionscenario behandlas möjligheten att bufferterosion skulle kunna leda till ett brott mot kriteriet för den hydrauliska konduktiviteten. I scenariot har det dock inte undersökts om en sådan erosion även kan leda till andra brott mot säkerhetsrelevanta kriterier som kan omfatta Buff1b (svälltryck >1 MPa) för att hålla en tät kontakt med det omgivande berget, Buff2 (”hög” täthet) att avsevärt skall minska mikrobiell aktivitet, och Buff5 (svullnad tryck >0,2 MPa) för att förhindra att en kapsel kan sjunka. Om scenarier där flera brott mot buffertsäkerhetsfunktioner som en följd av bufferterosion är möjliga, kan sådana scenarier bedömas som trovärdiga ”vad händer om” scenarier som påverkar kapselkorrosionsförloppet. En oberoende utvärdering som genomförts tyder på att även andra säkerhetsfunktionsindikatorkriterier inte skulle upprätthållas om advektiva förhållanden i bufferten skulle uppstå. Dessa inkluderar förlust av buffertens förmåga att upprätthålla en tät förslutning med berget (överträdelse av Buff1b) och, eventuellt, en förlust av buffertens förmåga att förhindra betydande mikrobiell aktivitet (överträdelse av Buff2). Förmågan av bufferten för att förhindra en sjunkning av kapseln (Buff5) behöver dock inte påverkas. Resultaten av denna analys tyder på att ”vad händer om” scenarier med kapselkorrosion kan behöva överväga eventuella förluster av flera säkerhetsfunktioner i bufferten samtidigt i stället för bara en säkerhetsfunktion i taget eller isolerat.

Projektinformation
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Diarienummer avrop: SSM 2013-2444
Aktivitetsnummer: 3030012-4064

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of this assignment is to explore various real and/or hypothetical corrosion situations in the repository environment with emphasis on its implications for canister life times. The scope is limited to corrosion mechanisms amenable for mass balance considerations (i.e. corrosion mechanisms related to mechanical loading such as stress corrosion cracking is excluded). The assignment should include flow and groundwater chemical conditions affecting canister corrosion, variants of buffer evolution and its impact on copper corrosion, and various corrosion and geochemical mechanisms.

Summary by the authors

This Technical Notes reviewed the issues that may cause canister corrosion other than the cases evaluated by SKB, which may belong to "What-if" canister corrosion scenarios. This Notes, in particular, addressed two potential canister corrosion scenarios: "wormhole" formation and loss of multiple buffer safety functions.

The "wormhole" scenario was hypothesized during the SSM Workshop on "What-if" Canister Corrosion and was based on FEP BU07 "piping and erosion of the bentonite buffer" scenario. The subsequent analysis found that the penetration time of the copper canister based on hypothetical size and location of the pipe is shorter than previously predicted. Note that the corrosion analysis was made by assuming that a pipe can be formed. No analysis of how the pipe could form and become stable was conducted. SKB's study indicated that the piping scenario is impossible for an intact buffer after the buffer is fully saturated. In the "wormhole" scenario, the formation of such a hole was based on the assumption that a locally high gradient of groundwater could contribute to the piping.

To address the "wormhole" concern, the Technical Note analyzed environmental conditions affecting the potential generation, stability and persistence of such localized buffer-erosion features. The focus is placed on the high hydraulic gradient and hence concentrated flow rates into deposition hole. For this purpose, a simple model was used to obtain the critical hydraulic gradient for a given range of buffer swelling pressure. The critical hydraulic gradient is defined as the minimum gradient required for maintaining an open pipe. The calculated critical hydraulic gradient ranges from 8.2 - 8.800 that is orders of magnitude higher than 10^{-6} – 1.0, the modelled ambient hydraulic gradient. This range is also generally higher than the ambient hydraulic gradient during glacial periods, ranging from 0.15 to 1.49. The lowest value, 8.2, corresponding to a partially eroded buffer, is still greater than the highest glacial gradient. Therefore, the formation of a wormhole across an intact bentonite buffer due to a high gradient is highly unlikely.

An issue related to “wormhole” formation and stability is the flow rate in fractures intersecting deposition holes. The speculation was that an alternative flow model, Sparse Channel Network (SCN) model, would yield significantly higher flow rate into a fraction of deposition holes than the Discrete Flow Network (DFN) model that was used in SKB SR-Site safety analysis. Consequently, these deposition holes would be more likely to form “wormhole” through buffer. The SCN model was considered because the modeling results were shown to fit field observations better than the DFN model. By evaluating the SCN model and results, it was found that there is no sufficient evidence to support the speculation. The primary reason lies in the model assumptions. The SCN model assumed a horizontal, open, cylindrical cavity with zero head and subject to a constant head boundary condition at a radial distance of 45-m away from the center of the cavity. The resulting hydraulic gradient is about 4.5 in the radial inward direction, which is not the post-closure condition of repository when buffers are all fully saturated and the ambient hydraulic gradient is resumed.

The last issue considers whether “what-if” scenarios of canister corrosion based on simultaneous losses of two or more buffer safety functions are feasible. The main driver for these scenarios is assumed to be a loss of buffer density caused by chemical (i.e., colloid related) erosion. SKB’s buffer advection scenario addressed the possibility that buffer erosion could lead to a violation of the hydraulic conductivity criterion. The scenario did not consider whether such erosion might also lead to other violations of safety-relevant criteria that could include Buff1b (swelling pressure > 1 MPa) to maintain a tight contact with the host rock, Buff2 (“high” density) to significantly reduce microbial activity, and Buff5 (swelling pressure > 0.2 MPa) to prevent canister sinking. If scenarios involving multiple violations of buffer safety functions as a result of buffer erosion are feasible, such scenarios could be evaluated as credible “what-if” scenarios affecting canister corrosion behavior. An independent assessment carried out suggests that other safety function indicator criteria could be violated should the buffer advective conditions arise. These include a loss of the buffer’s ability to maintain a tight seal with the rock (violation of Buff1b), and, possibly, a loss of the buffer’s ability to prevent significant microbial activity (violation of Buff2). The ability of the buffer to prevent canister sinking (Buff5) may not be affected, however. The results of this assessment suggests that “what-if” scenarios involving canister corrosion may need to consider possible losses of multiple safety functions of the buffer simultaneously rather than just one safety function at a time or in isolation.

Project information

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Contents

1. Introduction

In the SR-Site report (SKB, 2011, Chapters 11 and 12), SKB focuses on various scenarios that might affect the containment potential for their KBS-3 disposal concept. The purpose of such alternative scenarios was to aid in critical evaluation of the effectiveness and reliability of the KBS-3 concept to assure regulatory compliance for both containment and retardation release periods. Three canister scenarios were selected for analysis in SR-Site, including

- Canister failure due to chemical corrosion (Safety function Can 1),
- Canister failure due isostatic loading (safety function Can 2), and
- Canister failure due to earthquake shearing (Safety function Can 3).

SSM has conducted extensive technical reviews on all of these canister scenarios; this report addresses certain speculative aspects of the Can 1 scenario.

Building on the Can 1 scenario, SKB considers various *buffer states* that might further affect chemical corrosion of the copper canister. In particular, SKB (2011, Chapters 10.3.11 and 12.6) evaluate the case where the initial buffer may experience *chemical erosion*, in which buffer material might be removed during glacial periods when dilute melt waters might circulate to repository depths. Loss of buffer mass would translate into decrease in buffer density, which in turn could lead to progressive loss of safety functions of the buffer, including onset of advective flow through the buffer. Loss of buffer and on-set of advective conditions could elevate the rate of transport of dissolved bisulfide (HS^-) from the host rock to the surface of the copper canister, thereby increasing the rate of general corrosion of copper by HS^-. The rate of copper corrosion by bisulfide is also a strong, inverse function of the exposed surface area from buffer erosion; the smaller the exposed surface area to advective flow, the higher the general rate of copper corrosion from a more focused advective flux of bisulfide to this limited area (SKB 2010a).

With respect to the importance of advective flow affecting the erosion rate of buffer, hence the failure rates of canisters by general corrosion, SKB (2011, page 574) states their analyses show

"*Irrespective of the outcome of the complex interplay of a number of uncertain factors influencing the occurrence of buffer advection, the consequences in terms of canister failures are always bounded by the case where advection is assumed for all canisters throughout the assessment period, and these failure rates are similar to those for the reference evolution where only a small fraction of the deposition holes are affected by advective conditions in the buffer. The reason for this simplifying circumstance is that the time taken to erode the buffer to the extent that advection occurs is shorter than that required to cause corrosion failure once the advective conditions are established. For both processes, the groundwater flow rate at the deposition position in question is an important determining factor, and dependence on other factors influencing erosion and corrosion, respectively, is such that the time required to reach advective conditions is, in general, shorter than that required to cause corrosion failure once advective conditions are established. It is also noted again that it is only in the small number of holes that have high advective flow rates in the intersecting fractures that erosion and subsequent enhanced corrosion could lead to canister failures in one million years.*"

Unless buffer erosion were to occur relatively quickly and expose only a small area of the copper canister to advective flux of HS^- (i.e., buffer erosion occurring along a thin, open planar-feature or as a small open pipe ("wormhole") through the buffer (see Can 1 SSM Technical Note on August 2013 workshop), the SR-Site analyses for the Can 1 scenario, including eroded buffer state, show acceptably safe performance.

Therefore, one of the focuses of this report is on analysis of environmental conditions (high hydraulic gradient and concentrated flow rates into deposition hole) affecting the potential generation, stability and persistence of such localized buffer-erosion features, notably a hypothetical tube or "wormhole" geometry. The rationale for examining such a speculative case is that, if such a tube of eroded buffer were to develop, it likely would develop quickly and expose a small area of the copper canister to a relatively high advective flux of HS^-. Taken together, these impacts could possibly lead to significantly earlier chemical corrosion failure of the canister compared to the cases considered in SR-Site (SKB 2011, Chapter 12.6).

Another issue covered in this technical note is the scenario of losing multiple safety functions of buffer. SKB's analysis of buffer erosion considers only the impacts of bentonite mass loss from a deposition hole on the development of advective mass transport conditions in the buffer. Other safety function indicator criteria could, however, also be adversely impacted by buffer erosion even before such advective conditions were established. For example, if buffer erosion were to result in saturated densities sufficient to create advective conditions in the buffer, the buffer would also have lost enough density to prevent adequate tightness/self-sealing and to prevent significant microbial activity. This suggests that "what if" scenarios involving canister corrosion may need to consider possible losses of multiple safety functions simultaneously rather than just one safety function at a time or in isolation. The motivation was to determine whether scenarios involving multiple violations of buffer safety functions as a result of buffer erosion are feasible.

2. The “Wormhole” Issue

The “wormhole” in this note is defined as a small pipe formed across the buffer that would bring groundwater with corrodants in contact with the copper canister, initiating corrosion (Apted 2013; Stothoff and Manepally 2013). The hypothesis of “wormhole” was raised during the SSM workshop on “what-if” canister failure scenarios (Apted 2013). The “wormhole” scenario was derived from “piping and erosion of the bentonite buffer”, one of the SR-Site FEPs for the buffer (SKB 2010b).

2.1. SKB’s presentation

The definition of the “piping and erosion of the bentonite buffer” scenario can be found from SKB (2010b), repeated below:

“*During the resaturation process, if water pressure in the fracture is sufficiently high, the swelling bentonite is relatively soft, and space for removing bentonite particles available, formation of channels in the buffer is possible*.”

The initial concern of piping/erosion arises from phenomena of water-clay interactions during resaturation (SKB 2010c):

“*Water inflow into the deposition hole will take place mainly through fractures and will contribute to wetting of the buffer. However, if the inflow is localised to fractures that carry more water than the swelling bentonite can absorb, there will be a water pressure in the fracture acting on the buffer. Since the swelling bentonite is initially a gel, which increases its density with time as the water goes deeper into the bentonite; the gel may be too soft to stop the water inflow. The results may be piping in the bentonite, formation of a channel and a continuing water flow and erosion of soft bentonite gel. There will be competition between the swelling rate of the bentonite and the flow and erosion rate of the buffer*.”

Hence, piping across the buffer may take place and the pipe may remain open if the following three conditions are fulfilled at the same time:

1. The water pressure P_{wf} in the fracture, when water flow is prevented by the presence of the bentonite, must be higher than the sum of the counteracting confining pressure from the clay and the shear resistance of the clay;
2. The hydraulic conductivity of the clay must be so low that water flow into the clay is sufficiently retarded to keep the water pressure at P_{wf};
3. There is a downstream location available for the flowing water and the removal of eroded mass in order for the pipe to stay open.

Apparently, the conditions 1 and 2 cannot be satisfied at the same time in order for a pipe to form and remain open after buffer resaturation. This means that piping, if can occur, only occurs before the buffer is fully saturated and homogenized because swelling pressure of the material is very high. After saturation and homogenization of the buffer and restoring of the hydrostatic water pressure, the water pressure will be separated from the swelling pressure according to the effective stress theory. The pipes or openings caused by any initial erosion or defects will thus be sealed and a swelling pressure established if the density and resulting swelling pressure are high enough to overcome internal friction. Later on, there is very little chance of piping because piping requires a strong and fast increase in water pressure gradient locally in the rock at the contact with the buffer.

2.2. Motivation of the assessment

As stated in Section 2.1, SKB's analysis showed that it is unlikely that a pipe would form across an intact buffer. Nevertheless, the "wormhole" scenario was hypothesized based on FEP BU07 (Section 2.1) "piping and erosion of the bentonite buffer" scenario. The subsequent analysis found that the penetration time of the copper canister based on hypothetical size and location of the pipe is shorter than previously predicted (Stothoff and Manepally 2013; Apted 2013). Note that the corrosion analysis was made by assuming that a pipe can be formed. No analysis of how the pipe could form and become stable was conducted.

The hypothesis was critically assessed during the workshop. Some workshop attendees doubted the likelihood of a sustained pipe. The hypothesizer assumed that a locally high gradient of groundwater could contribute to the piping. Following the workshop, some SSM members who attended the workshop became concerned and questioned whether or not such a pipe can form. In this section, the issue will be examined through the groundwater gradient.

2.3. The Consultants' assessment

First of all, the consultants agree with the SKB's presentation presented in Section 2.1. In this sub-section, the pressure gradient of groundwater required to break through and overcome the swelling bentonite was estimated and was compared with the site data (modelled or measured). As shown in Figure 1, a pipe was assumed to form due to a fracture channel across the deposition hole. The fracture channel was assumed to have a circular cross section, which means that the pipe formed inside the buffer was a circular pipe. At the entrance of the pipe, i.e., the interface between rock and bentonite, the water pressure is assumed to be P_{wf} and the swelling pressure is assumed to be P_b. The hydrostatic pressures across the interface are the same. Therefore, when $P_{wf} < P_b$, the swelling bentonite extrudes into the fracture channel. When $P_{wf} = P_b$, the forces from the two pressures balance each other. We denote the water pressure that is just sufficient to balance the swelling pressure as the *critical fracture water pressure*: P_{wfc}. Any water pressures $P_{wf} > P_{wfc}$ would result in water flowing towards the bentonite, which may create a pipe assuming that the bentonite in contact with the fracture water is gel and the friction force holding the bentonite particles together is negligible. Furthermore, the fracture channel downstream of the buffer was assumed to be open and capable of transporting any bentonite eroded from the buffer.

The swelling pressure of the buffer depends on bentonite density. Using the Base Case values (SKB 2011), the swelling pressure is approximately 7 MPa at 2000 kg/m^3 saturated density. According to the erosion sensitivity case (SKB 2011), if the saturated density decreases to 1500 kg/m^3, the swelling pressure decreases to 0.08 MPa. The relevant range of P_{wfc} values is thus 0.08 – 7 MPa.

Estimating the local pressure gradient can be problematic. In this assessment, we used the longest pipe length to estimate the minimum pressure gradient required for water to intrude the bentonite and overcome the swelling pressure that tends to reseal the pipe. Referring to Figure 1, the longest horizontal pipe would be the one tangential to the canister surface. Giving the radii of the canister and buffer outer surfaces, R_1 and R_2 (Figure 1) respectively, the length L can be estimated:

$$L = 2\sqrt{R_2^2 - R_1^2} \qquad (1)$$

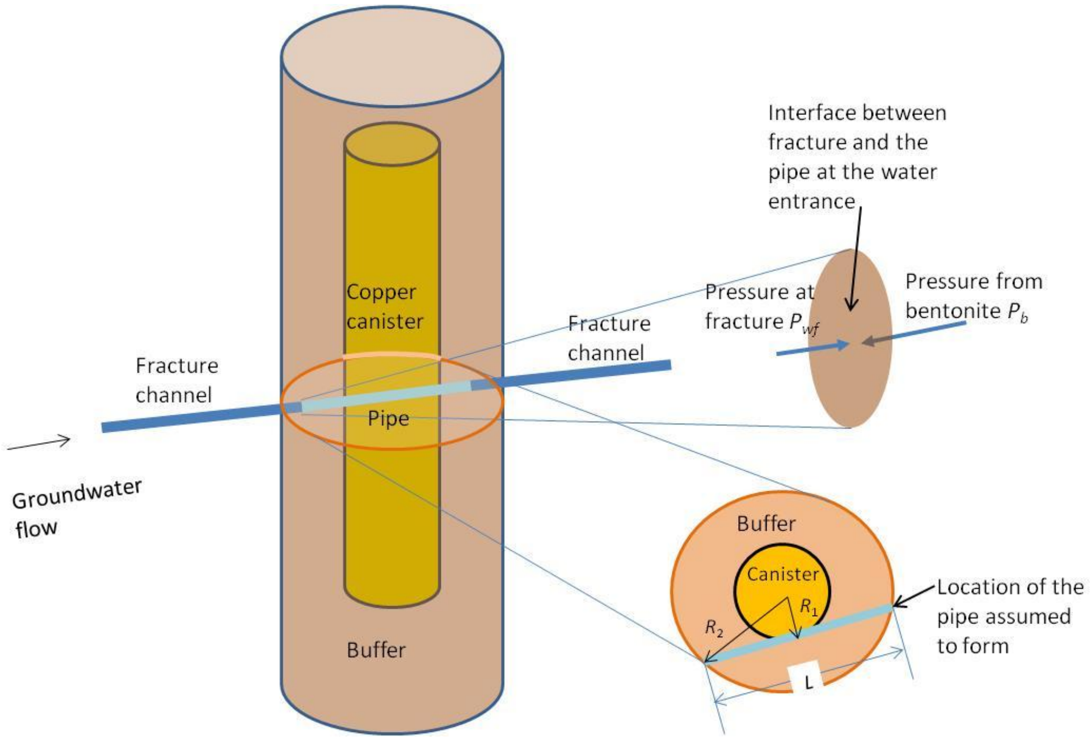

Figure 1. Illustration of a hypothetical "wormhole" in the buffer used in the assessment. The top right small cross section illustrates pressure balance before the pipe forms. The bottom right cross section illustrates the pipe that was assumed to form and remain open. R_1 is the radius of the copper overpack [m], R_2 is the buffer outer radius [m], and L is the length of the hypothetical pipe.

Assuming R_1 = 0.525 m (SKB 2010a), R_2 = 0.875 m (for a 0.35 m thick buffer), Equation (1) gives L = 1.4 m.

The minimum pressure gradient across the pipe is

$$\frac{\Delta P}{L} = \frac{\Delta h \rho g}{L} = i\rho g \qquad (2)$$

where ΔP is the pressure drop across the pipe [Pa], Δh is the hydraulic head drop across the pipe [m], ρ is the water density (assumed to be 1000 kg/m^3), g is the gravitational accelerator (9.8 m/s^2), and i is hydraulic gradient [-] defined as:

$$i = \frac{\Delta h}{L} \qquad (3)$$

From (2) and the definition of P_{wfc}, the range of the minimum gradient required to open and maintain the pipe shown in Figure 1 can be estimated as:

$$i_{min} = \frac{P_{wfc}}{L\rho g} \quad (4)$$

Here we have assumed that at the exit of the pipe, the fracture water pressure is the same as the local hydrostatic pressure, which is reasonable for a presumably open fracture to remove bentonite mass eroded by water flowing through the pipe.

For swelling pressures ranging from 0.08 – 7 MPa, i_{min} = 8.2 - 8,800 [-], respectively. To keep the pipe open, the minimum gradient must be constant over time. The only way to sustain the gradient is through the ambient, or the background, gradient. That is, if the required gradient to keep the pipe open is equal to the ambient gradient, the gradient can be kept constant. Therefore, we will compare the calculated i_{min} with the ambient gradient range.

The calculated i_{min} range is orders of magnitude higher than 10^{-6} – 1.0, the modelled ambient hydraulic gradient (SSM 2011). This range is also generally higher than the ambient hydraulic gradient during glacial periods (SKB 2011), ranging from 0.15 to 1.49. The lowest value of i_{min}, 8.2, corresponding to a partially eroded buffer, is still greater than the highest glacial gradient.

Note that the lowest i_{min} calculated in this analysis corresponds to a partially eroded buffer (the saturated density decreasing to 1500 kg/m^3). SKB (2011) cited a research that piping was observed when the swelling pressure drops to 0.06 MPa. It is unclear, however, that at what circumstances the piping was observed in the experiment or modelling. Nevertheless, at this swelling pressure, the minimum hydraulic gradient across the hypothetic pipe, calculated from Equation (4), is 4.37, which is still greater than the maximum gradient during glacial periods. It was also reported that at this swelling pressure, the advective condition can prevail to carry corrodants to the canister surface. In this regard, the formation of a pipe does not play a significant role to further worsen the corrosion.

Note that the analysis presented in this section differs from the "wormhole" analysis presented in the Workshop (Apted 2013; Stothoff and Manepally 2013) in which a wormhole is assumed to exist in the buffer intersected by a planar fracture. It was further assumed that only a fraction of the background hydraulic gradient is drawn to the wormhole. This causes a portion of water, supposed to flow around the deposition hole in the fracture plane, to be funnelled into the wormhole *if* a wormhole had already formed. In contrast, the analysis presented in this section assumed that the intersecting fracture is a narrow channel (see next section) and indicated that even the 100% background hydraulic gradient is not sufficient to generate a pressure rise to balance or overcome the swelling pressure of the bentonite buffer, let alone a smaller fraction of background hydraulic gradient that would be too weak to balance or overcome the swelling pressure. Therefore, the formation of a wormhole across an intact bentonite buffer is not possible.

3. Deposition holes encountering high flow rates

Section 2 indicates that forming a pipe through the intact buffer requires extremely high flow rates (or hydraulic gradients) of groundwater delivered by the intersecting fractures. The high flow rate would also contribute to buffer erosion through colloidal transport. This section is dedicated to assessing one of the alternative flow models that was perceived to predict significantly higher flow rates in the fractures intersecting the deposition borehole than SKB's DFN model prediction.

3.1. SKB's presentation

In SKB (2011, page 574), it is stated:

"*In the reference evolution, advection as a transport mechanism in the buffer is assumed to the extent suggested by the results of calculations of the base case for the reference evolution in Section 10.3.11, where 23 out of approximately 6,000 deposition positions are calculated to experience advective conditions within one million years for the base case realisation of the semi-correlated hydrogeological DFN model*."

This section also reviewed SKB's Sparse Channel Network (SCN) model. The Sparse Channel Network (SCN) model is selected because the SCN results were shown to fit field observations better than the DFN model (Black et al., 2006; 2007; 2013). In Black et al. (2013), the authors stated:

"*The Stripa observations have existed for many years yet, to date, no model has indicated an apparent skin effect next to underground openings in fractured crystalline rocks except where local values of conductivity have been specifically altered. During this time, it has become common practice to simulate groundwater flow in fractured crystalline rocks using increasingly complex 'discrete fracture network' (DFN) models. To date, DFN models have not reproduced regions of apparently reduced hydraulic conductivity around underground openings*."

This motivated Black et al. to use SCN approach to simulate the flow field with an open tunnel or drift and compare with the Stripa observation. A "*channel*" in the study was defined as a continuous flow path that is significantly elongated in one direction with aspect ratios in the order of 10:1 or more. A channel may represent lines formed by two or more intersecting planar fractures. The channel may consist of connected sub-channels. The "*sparseness*" in the model meant that the highly non-equidimensional channels have a moderate frequency of occurrence (or density) but a low chance of interconnection. Black et al (2006; 2007; 2013) used a three-dimensional lattice network model and the statistical method to generate various realizations of channel network with different sizes and channel densities. Figure 2 shows an example on how the channel network was created using the lattice network. The channels, represented as dark lines in Figure 2, consist of the connected "bonds" on the lattices.

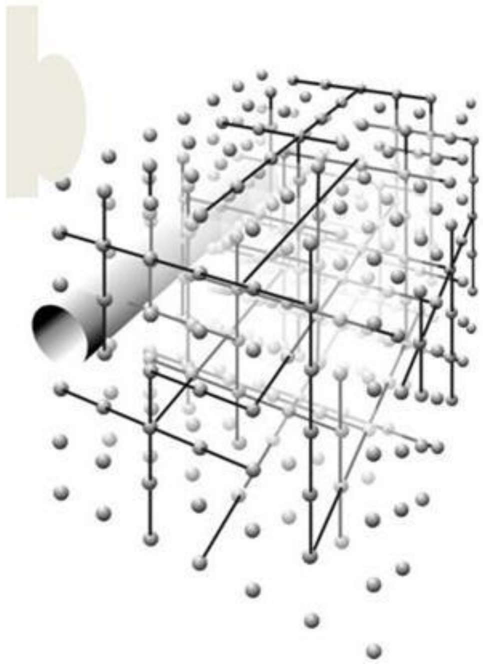

Figure 2. An example of Sparse Channel Network generated by 3D lattice network model. Channels are represented by dark lines, i.e., the connected bonds at the lattice corners (Black et al., 2013).

The model used the Thiem equation to simulate steady state flow towards an inner cylindrical boundary (set as zero head) from an outer cylindrical boundary with constant head. The Thiem equation includes the skin effect. The skin effect is related to the surface effects of the flow channel, i.e., fractures, which could decrease hydraulic conductivity (a positive skin effect) or increase hydraulic conductivity (a negative skin effect) near the open tunnel. Large scale hydraulic conductivity and skin effect values were calculated for ensembles of mostly 100 realizations over a range of values of channel size and network density. Only certain ensembles of all realizations resulted in percolation, i.e., water flows from the outer boundary to the inner boundary (the tunnel wall) as shown in Figure 3.

The authors reported that the SCN model is able to simulate the skin effect near the open tunnel, as well as the compartmentalized (step changes in) or clustered head and groundwater composition distributions. The latter was observed in other studies and field data (Black et al., 2013). The authors concluded that the main reason for the modelling results resembling the field observations was related to the sparseness of the channel network. The sparse channel network resulted in “hyper-convergence” of the flow, which was observed at Stripa URL and can be illustrated in Figure 4. When groundwater flows into a drift in fractured crystalline rock, there are only a limited number of inflow points towards which the inflowing water must converge as shown in Figure 4(a). Previously, it was believed that the flow field is one-dimensional in cylindrical coordinate system in radial direction only with a uniform sink in the interior boundary such as that shown in Figure 4(b). The SCN model reveals, however, that the flow field is three-dimensional, i.e., the typical flow rate towards the interior boundary has components in radial, tangential, and axial directions. Flow thus converges to a few points along the axial direction of the open cavity. This convergence is extra to that of the one-dimensional radial flow, and hence termed “hyper-convergence”. It causes “extra” head loss and is usually perceived as the skin effect that reduces the hydraulic conductivity.

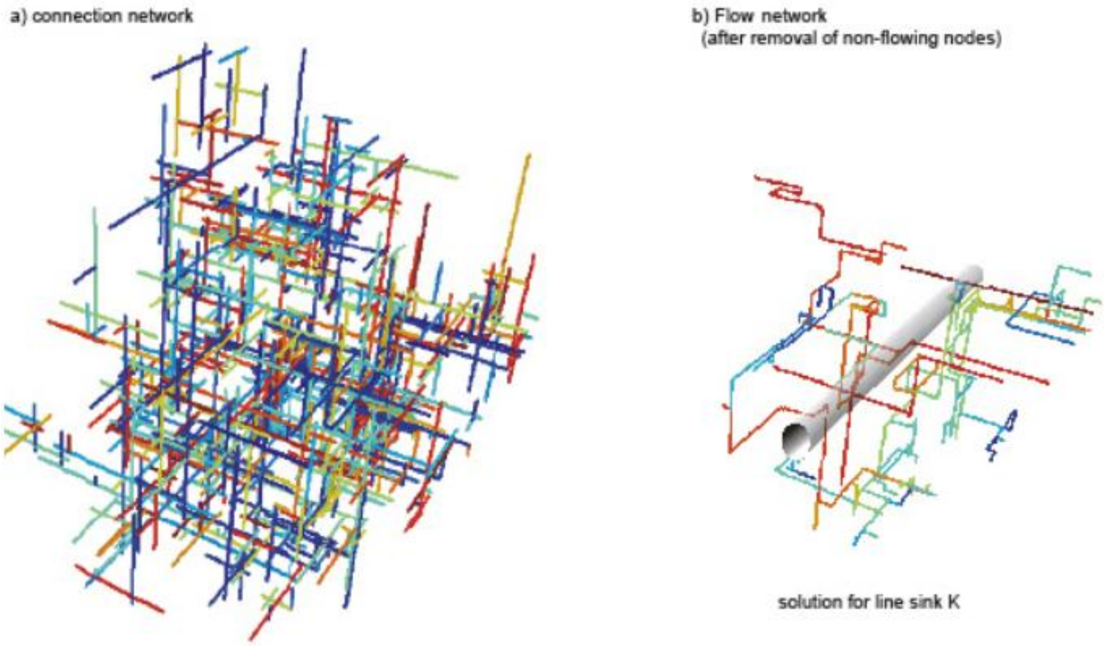

Figure 3. Example of how a sparse network of connections, shown in (a) is reduced to an even sparser flow network shown in (b). Note that the modelled system is a cylinder of 90-m diameter as the outer boundary and the drift is 4-m diameter as the inner boundary (Black et al., 2006). Different colors represent different networks.

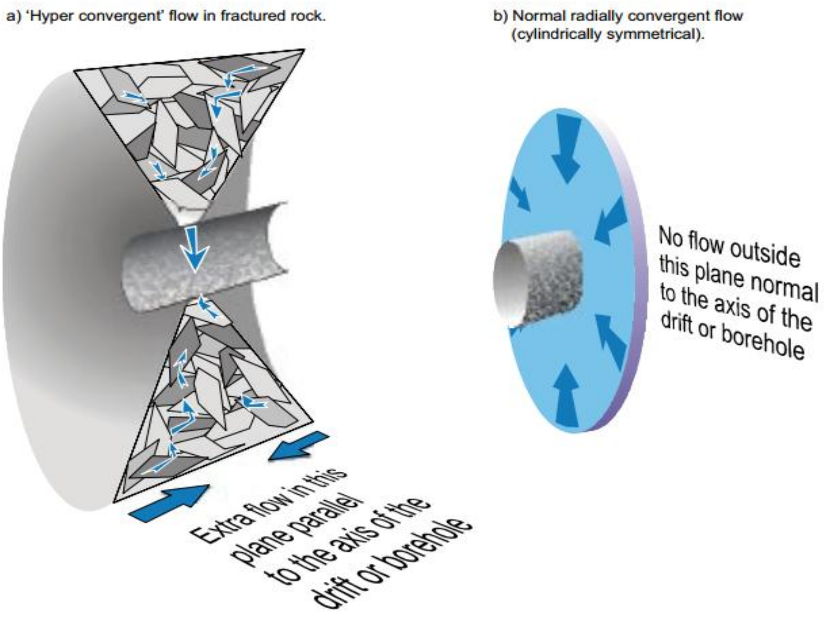

Figure 4. Comparison of (a) three-dimensional flow with hyper-convergence and (b) one-dimensional radial flow (Black et al., 2006).

Black et. al. (2013) provided a visual comparison between a SCN realization with active flow channels that fits observations at Stripa and a DFN model of “background fractures” at the Äspö URL, as shown in Figure 5. Although Figure 5(a) shows only the channels with active flow from the SCN model, whereas the DFN model includes all hydraulically connected fractures shown in Figure 5(b), the difference in density can be observed. Note that both (a) and (b) in Figure 5 actually have the same scale. In the SCN model shown in Figure 5(a), only 90-m diameter cylindrical modelling domain is illustrated. One should compare Figure 5(a) with the 90-m diameter cylindrical domain in the centre of Figure 5(b). Due to extremely dense fracture network in DFN, this comparable domain is not visible in Figure 5(b) nor the borehole in the middle and its intersection with fractures can be visible. Nevertheless, the fundamental difference in fracture densities can be demonstrated.

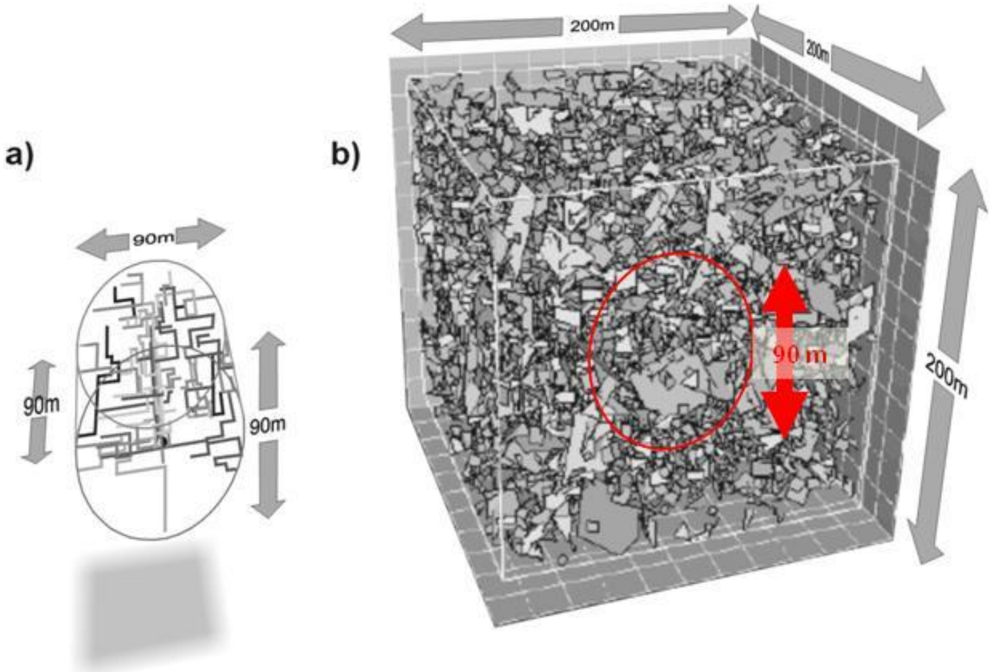

Figure 5. Comparison of a) a sparse channel network representing groundwater flow at the Stripa URL and b) a DFN model of “background fractures” at the TRU Block tracer experiment at Äspö (Black et al., 2013). Note that both images are at the same scale.

3.2. Motivation of the assessment

During the August 2013 Workshop in SSM on canister corrosion what-if scenarios (Apted 2013), the alternatives to SKB’s DFN model were discussed. These alternative models, in particular, included the SCN model by Black et al. (2006; 2007; 2013) because the SCN results were shown to fit field observations better than the DFN model. The SCN model would be expected to yield significantly higher flow rate into a fraction of deposition holes and to be more likely to form a “wormhole” through buffer if the model can be applied to the Forsmark site (Apted 2013). This motivated the consultants to investigate the applicability of the model and results to the repository at Forsmark.

3.3. The Consultants' assessment

This comparison shown in Figure 5 indicates that the channels of active flow are so infrequent that intersection between flowing channels and the open tunnels are sparse, especially compared with DFN model predictions. The researchers (Black et al., 2013) believed that the sparse channel network resembles the actual fracture network in crystalline rock better than the DFN model. If so, the number of deposition holes encountering high flow rates *cannot* be greater than the DFN model prediction. This means that DFN model results may represent a conservative approximation in the number of deposition holes encountering high flow rates.

The next issue is the flow rates of groundwater into the intersected deposition holes. The SCN modelling results by Black et al (2006, 2007, and 2013) seemed to suggest that the flow rates into the limited inflow points would be significantly higher than the DFN model predictions due to the nature of "hyper-convergence" in the flow field of represented by SCN model as illustrated in Figures 4 and 5. Cautions must be applied when applying the flow rates predicted by Black et al (2006, 2007, and 2013) to the repository host rock at Forsmark.

Black et al (2006, 2007, and 2013) model studies steady state flow field in a cylindrical coordinate system surrounding an open cavity as shown in Figure 6(a). The inner boundary is equal to the cavity radius, assumed to be 2 m, and has a constant zero head. The outer radius of the modelling domain is assumed to be 45 m and has a constant head of 200 m, giving rise to a hydraulic gradient of 4.65 in radial inward direction. The modelling domain with the head distribution resembles the Stripa mine condition. In the repository, the Black et al's modelling system can be considered to resemble the condition during the repository construction phase when the tunnel and deposition hole have not been backfilled and sealed. Presumably, the deposition holes with "hyper-convergence" of flow would visibly show high flow rate and thus would be rejected. Long after post-closure of the repository, the tunnel backfills and the buffer in deposition holes are saturated, hydrostatic pressure distribution is restored, and the hydraulic gradient follows that of the background. There will be no open cavity and zero head boundary conditions at the tunnel and borehole surfaces. Furthermore, the saturated backfills in the tunnel and buffers in the deposition holes are in fact the impervious boundaries. Under these conditions, the actual flowing channel network may not be that shown in Figure 5(a). Rather, groundwater would "detour", i.e., preferentially choose a network (e.g., from all the connected channels shown in Figure 3(a)) that would be along the given gradient and around the impervious tunnel and deposition holes, as illustrated in Figure 6(b). Hence, it is highly unlikely for "hyper-convergence" to occur at the tunnel or deposition holes.

In summary, the consultants found that the SCN modelling results reported in Black et al. (2013) do not imply significantly higher flow rates to the intersected deposition holes than the SKB's DFN modelling results. Because the high flow rate of groundwater through intersecting fracture is a necessary condition for forming a sustained "wormhole" through the buffer, it can be, therefore, concluded that the alternative SCN model does not promote the likeliness of the "wormhole" scenario. The consultants hence found that the current SKB's DFN modelling results on buffer erosion and the subsequent impacts on canister corrosion are not invalidated solely based on the "wormhole" hypothesis.

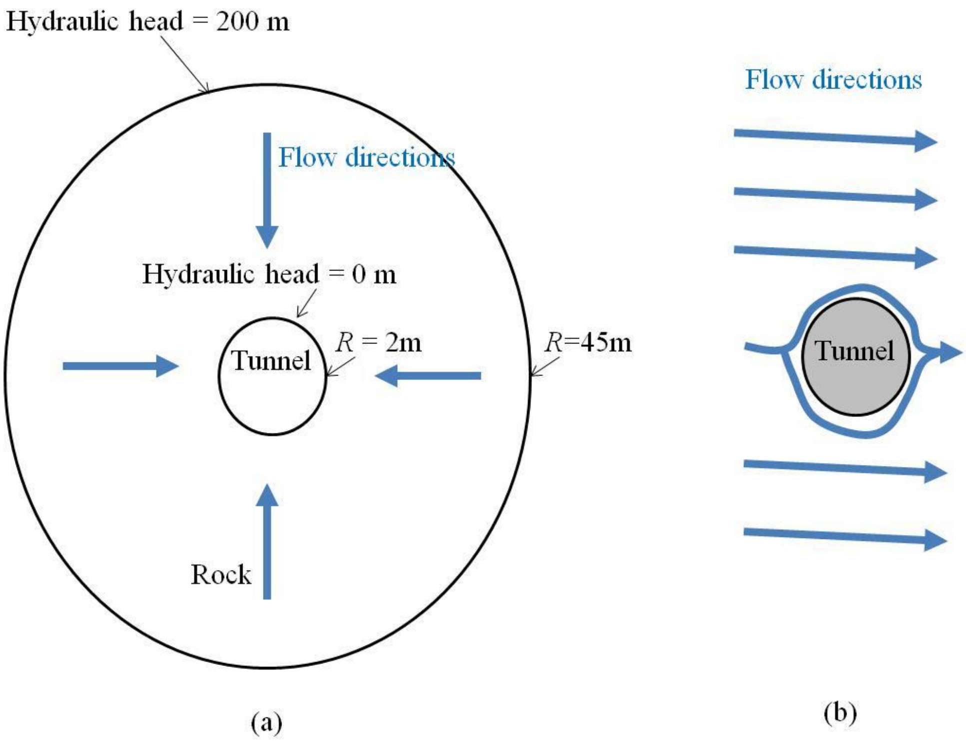

Figure 6. (a) Illustration of the boundary conditions and the modeling system in radial direction of the Sparse Channel Network model by Black et al (2006; 2007; and 2013) that deals with an open tunnel. *R* are the radii of inner and outer boundaries. (b) In contrast, the repository tunnel after resaturation is a no-flow boundary.

4. "What if" scenarios of canister corrosion based on multiple losses of buffer safety functions

Buffer safety functions that are directly related to canister corrosion include (see Figure 7, where corresponding safety function indicator criteria are also noted):

- Buff1: Limit advective transport;
- Buff2: Reduce microbial activity;
- Buff4: Resist transformation; and
- Buff5: Prevent canister sinking.

Quantitative limits have been established by SKB for all safety function indicator criteria except for Buff2, which specifies only that the buffer density must be "high". SKB believes that specifying a more precise criterion for Buff2 is not possible because a number of factors may play a role in controlling microbial activity (e.g., density variations in the buffer) (SKB, 2011; p. 255).

This section considers whether "what-if" scenarios of canister corrosion based on simultaneous losses of two or more buffer safety functions are feasible. The main driver for these scenarios is assumed to be a loss of buffer density caused by chemical (i.e., colloid related) erosion (or possibly by wormholes).

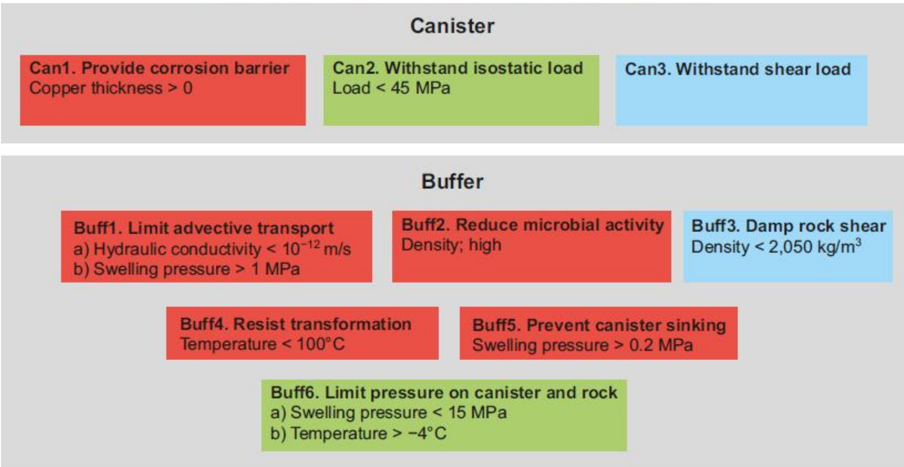

Figure 7. Containment related safety functions, safety function indicators, and safety function indicator criteria for the canister and buffer (based on Figure 8-2 of SKB, 2011). The colour coding relates to canister safety functions Can1 (red), Can2 (green), and Can3 (blue).

4.1. SKB's presentation

The "buffer advection" scenario in SR-Site (SKB, 2011; Section 12.2) addresses a possible violation of the buffer hydraulic conductivity criterion (Buff1a, Figure 7) caused by a loss of buffer density due to a loss of buffer material from a deposition hole. The loss of buffer material was assumed to result from the formation and release of clay colloids from bentonite that extrudes into fractures intersecting a deposition hole. This loss mechanism is referred to as “erosion”. Other mechanisms, including the effects of piping or expansion of the buffer from a deposition hole into the overlying backfill, were not considered.

The amount of buffer that would have to be eroded from a deposition hole before advective conditions could arise was assumed to be 1,200 kg (SKB, 2011; Section 10.3.9). The erosion rate was estimated using:

$$R_{erosion} = A\delta v^{0.41}, \quad (5)$$

where $R_{erosion}$ stands for the erosion rate, v represents the groundwater velocity in a fracture intersecting the buffer, δ denotes the fracture aperture, and A is a constant (SKB, 2011; Section 10.3.11). Values for v and δ were obtained from groundwater flow calculations. The natural variability in these parameters was estimated by determining flow conditions in each of the ensemble of 6,000 deposition holes in the repository. The flow calculations were carried out using SKB’s hydrogeological DFN model with a semi-correlated relation between fracture length and transmissivity (SKB, 2011; Section 10.3.6). The fraction of time during which erosion occurs was assumed to be 25% of the time in the 2% of deposition holes exposed to the highest flow rates (SKB, 2011; Sections 10.3.7 and 10.4.7).

The erosion model was used by SKB to predict that 0.6 deposition holes would experience advective conditions after 100,000 years. About 20 deposition holes would experience such conditions by the end of the one million year assessment period.

Uncertainties in the buffer erosion model are significant (e.g., SKB, 2011; p. 574). Two bounding cases were therefore defined by SKB to complement the “reference” case discussed above:

- a case in which advective conditions are assumed to occur in every deposition hole throughout the assessment period; and
- a case in which diffusive conditions are preserved in every deposition hole throughout the assessment period.

Canister failures predicted when all deposition holes were assumed to be advective throughout the assessment period were similar to the small number of failures predicted in the reference case. This is because the time required to erode the buffer sufficiently for advective conditions to occur is short compared to the time required for a canister to fail by corrosion. This result highlights the importance of the flow rate and sulphide content of groundwater in fractures at specific deposition-hole locations as key controls on canister longevity.

4.2. Motivation of the assessment

SKB’s buffer advection scenario addressed the possibility that buffer erosion could lead to a violation of the hydraulic conductivity criterion (Buff1a, Fig 7). The scenario did not consider whether such erosion might also lead to other violations of safety-relevant criteria. Such other criteria could include Buff1b (swelling pressure

> 1 MPa) to maintain a tight contact with the host rock, Buff2 (“high” density) to significantly reduce microbial activity, and Buff5 (swelling pressure > 0.2 MPa) to prevent canister sinking. The motivation for the present assessment was to determine whether scenarios involving multiple violations of buffer safety functions as a result of buffer erosion are feasible. If so, such scenarios could be evaluated as credible “what if” scenarios affecting canister corrosion behaviour.

4.3. The Consultants’ assessment

The key safety function indicators in Buff1b, Buff2, and Buff5 are the buffer density [ρ; saturated (or dry)], hydraulic conductivity (K), and swelling pressure (P_{swell}). The present assessment is thus based on relations among these parameters.

An empirical approach to understanding these relations is illustrated in Figure 8, which is based on work carried out in the Finnish KBS-3 R&D program (Posiva, 2010). The figure is drawn in terms of P_{swell} and K as a function of ρ. The solid blue line shows measured changes in P_{swell} as a function of ρ for MX-80 bentonite in contact with a 1 M NaCl solution at approximately 25^{o}C (SKB, 2006). The solid red line shows corresponding results for K. The density-dependant changes in P_{swell} and K are related to safety functions, safety function indicators, and safety function indicator criteria (i.e., following SKB’s terminology) by the corresponding dashed blue and red lines. These parameters are generally similar in the Finnish and Swedish repository programs, but some differences are apparent.

For illustration purposes, the results in Figure 8 can be related to the Swedish KBS-3 concept using the criteria summarized in Figure 7. SKB’s Buff1a criterion ($K < 10^{-12}$ m/s) would thus not be met if ρ is less than about 1600 kg/m^3 (noting uncertainties in reading the x-axis tick marks in Figure 8), Buff1b (P_{swell} > 1 MPa) would not be met if ρ is less than about 1700 kg/m^3, and Buff5 would not be met if ρ is less than about 1550 kg/m^3. Moreover, although SKB’s criterion Buff2 is qualitative (ρ must be “high”), the results in Figure 8 suggest that significant microbial activity could occur if ρ is less than about 1,800 kg/m^3.

This assessment example suggests that should advective conditions arise in the buffer as a result of buffer erosion (violation of Buff1a; $\rho < 1,600$ kg/m^3), the buffer would also not be able to maintain a tight seal with the rock (violation of Buff1b; $\rho < 1,700$ kg/m^3), and could also permit significant microbial activity (possible/likely violation of Buff2, e.g., if $\rho < 1,800$ kg/m^3). The ability of the buffer to prevent canister sinking (Buff5; $\rho < 1,550$ kg/m^3) may be unimpaired, however. The combined effects of such multiple losses in buffer safety functions were not addressed in SR-Site (SKB, 2011), and could thus serve as a basis for defining credible alternative “what-if” scenarios potentially affecting canister corrosion behaviour.

The assessment approach described above is illustrative. For more rigorous and complete application of the approach, a series of curves similar to those shown in the Figure 8 should be constructed based on measurements over as broad a range of repository-relevant experimental conditions as possible. The family of curves defined in this manner should then be evaluated in relation to the safety function indicator criteria for Buff1a, Buff1b, Buff2, and Buff5.

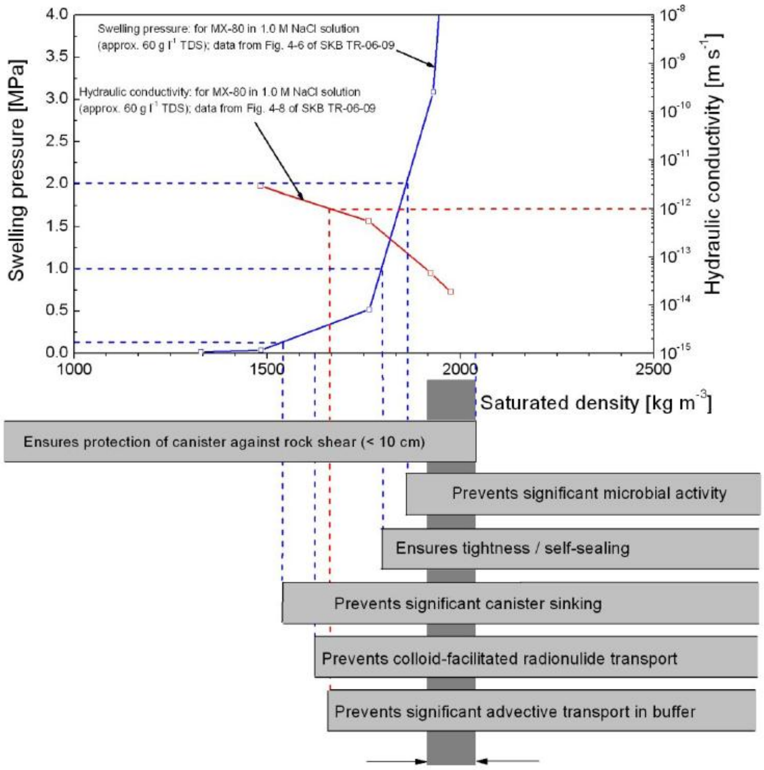

Figure 8. Diagram illustrating the effects of saturated density on the swelling pressure, hydraulic conductivity, and related safety functions of the buffer in a KBS-3 repository (Posiva, 2010).

5. The Consultants' overall assessment

In general, the consultants believe that the "wormhole" hypothesis is neither credible with respect to the *formation* nor *persistence* of such localized channels forming within compacted bentonite buffer. The necessary condition for a stable wormhole to be developed is when the buffer loses redistribution ability due to colloidal erosion of the buffer in the deposition hole intersected by a planar fracture. At this condition, the dominant process, or the more credible scenario, would be the cavity development and growth, which is more important to corrodants transfer to the copper overpack than a small pipe.

As for the alternative SCN flow model, exploring conceptual model uncertainty is helpful to enhancing confidence and resolving the "what-if" issues. Although the SCN modelling results agree with the Stripa mine observations, especially when compared with the DFN model, the conceptual model system does not represent the disposal system long after repository closure when all the backfills and buffers are saturated. Therefore, while the implication of sparseness may still be applicable to the crystalline hostrock at Forsmark, applying the "hyper-convergence" inflow towards an open tunnel directly to the saturated repository tunnel is questionable. It is recommended that SKB carry out the SCN modelling for the impervious interior radial boundary and background hydraulic gradient using the existing lattice network model. The outcome of active flowing channel network intersecting the tunnel and the flow rates would be more comparable to the current SKB's DFN model results.

On the issue of multiple loss of buffer safety functions, SKB's analysis of buffer erosion/canister corrosion in SR-Site (SKB, 2011; Section 12.2) considers only the impacts of bentonite mass loss from a deposition hole on the development of advective transport conditions in the buffer. An independent assessment carried out in the present study suggests, however, that other safety function indicator criteria could also be violated should such advective conditions arise. These include a loss of the buffer's ability to maintain a tight seal with the rock (violation of Buff1b), and, possibly, a loss of the buffer's ability to prevent significant microbial activity (violation of Buff2). The ability of the buffer to prevent canister sinking (Buff5) may not be affected, however. The results of this assessment suggests that "what-if" scenarios involving canister corrosion may need to consider possible losses of multiple safety functions of the buffer simultaneously rather than just one safety function at a time or in isolation.

6. References

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SSM (2011) "2011-2426-130 spreadsheet".

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APPENDIX 1

Coverage of SKB reports

This technical note is primarily dedicated to examining the “wormhole” scenario hypothesized by Stothoff and Manepally (2013). Although SKB’s reports are not the primary target of review, the relevant reports were reviewed and referenced, as indicated in Table 1.1.

Table 1:1 SKB reports reviewed or referenced

Reviewed report	Reviewed sections	Comments
TR-11-01	Chapters 8, 10, 11, and 12.	Referenced in Section 1, 2, and reviewed in Section 4.
TR-10-66	Chapter 4	Referenced in Section 1
TR-10-45	SR-Site FEP Bu07 Piping/erosion	Referenced in Section 2
TR-10-47	Section 3.3.4 Piping/erosion	Referenced in Section 2
TR-11-01	Section 10.3.9	Swelling pressure referenced in Section 2
TR-10-66	Chapter 2	Copper canister dimension referenced in Section 2
TR-11-01	Section 8.4.6	Piping experimental results at low buffer density referenced in Section 2
R-06-30	Sections 4 and 5	Reviewed in Section 3
R-07-35	Sections 3 – 11	Reviewed in Section 3

2014:39

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