Technical Report

TR-09-22

Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses

Svensk Kärnbränslehantering AB

November 2009

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1404-0344
SKB TR-09-22
ID 1188478
Updated 2013-01

Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses

Svensk Kärnbränslehantering AB

November 2009

The original report, dated November 2009, was found to contain editorial errors which have been corrected in this updated version.

Contents

1 Introduction

This document provides design premises from a long term safety aspect of a KBS-3V repository for spent nuclear fuel, based on the experience from SKB's latest published safety assessment, SR-Can, and some subsequent analyses. The elaboration is an expansion of the treatment of design basis cases and feedback to canister and repository design in sections 13.4–13.6 of the SR-Can Main report, SKB TR-06-09. The purpose is to provide more detailed material for the formulation of requirements on barriers and for actual design decisions. In some cases, the material builds on additional analyses carried out after the SR-Can project.

1.1 Objectives and scope

The objective with this report is to:

- provide design premises from a long term safety aspect of a KBS-3V repository for spent nuclear fuel, to form the basis for the development of the reference design of the repository.

The design premises are used as input to the documents, called production reports, that present the reference design to be analysed in the long term safety assessment SR-Site. It is the aim that the production reports should *verify* that the chosen design complies with the design premises given in this report, whereas this report takes the burden of justifying why these design premises are relevant. The more specific aims and objectives with the production reports are provided in these reports.

1.2 Approach

The following approach is used:

- The reference design analysed in SR-Can is a starting point for setting safety related design premises for the next design step.
- A few design basis cases, in accordance with the definition used in the regulation SSMFS 2008:21[1] and mainly related to the canister, can be derived from the results of the SR-Can assessment. From these it is possible to formulate some specific design premises for the canister.
- The design basis cases involve several assumptions on the state of other barriers. These implied conditions are thus set as design premises for these barriers.
- Even if there are few load cases on individual barriers that can be directly derived from the analyses, SR-Can provides substantial feedback on most aspects of the analysed reference design. This feedback is also formulated as design premises.
- An important part of SR-Can Main report is the formulation and assessment of safety function indicator criteria. These criteria are a basis for formulating design premises, but they are not the same as the design premises discussed in the present report. Whereas the former should be upheld throughout the assessment period, the latter refer to the initial state and must be defined such that they give a margin for deterioration over the assessment period. The basic approach for prescribing such margins is to consider whether the design assessed in SR-Can Main report was sufficient to result in safety. In case this design would imply too strict requirements, and in cases the SR-Can design was judged inadequate or not sufficiently analysed in the SR-Can report, some additional analyses have been undertaken to provide a better basis for setting the design premises.

The resulting design premises constitute design constraints, which, if all fulfilled, form a good basis for demonstrating repository safety, according to the analyses in SR-Can and subsequent analyses. Some of the design premises may be modified in future stages of SKB's programme, as a result of analyses based on more detailed site data and a more developed understanding of processes of

[1] Replacing SKIFS 2002:1 since December 19 2008.

importance for long-term safety. Furthermore, a different balance between design requirements may result in the same level of safety. This report presents one technically reasonable balance, whereas future development and evaluations may result in other balances being deemed as more optimal.

It should also be noted that in developing the reference design, the production reports should give credible evidence that the final product after construction and quality control fulfils the specifications of the reference design. To cover uncertainties in production and quality control that may be difficult to quantify in detail at the present design stage, the developer of the reference design need usually consider a margin to the conditions that would verify the design premises, but whether there is a need for such margins lies outside the scope of the current document.

The term "withstand" is used in this document in descriptions of load cases on repository components. The statement that a component withstands a particular load means that it upholds its related safety function when exposed to the load in question. For example, if the canister is said to withstand a particular corrosion load, this means that it will uphold its containing function when exposed to this load. The time period during which the safety functions are assessed is one million years after repository closure in accordance with applicable regulations. A more detailed and qualitative description of the safety functions is given in Chapter 4 of this document and in the Main report of the SR-Can assessment.

1.3 Structure of the document

Chapter 2 deals with derivation of design basis cases, as these are defined in SSM's regulations, and describes the design bases cases. Chapter 3 derives safety related design premises on the barriers based on findings from the design basis cases and other feedback from SR-Can. Chapter 4 briefly discusses how the resulting design premises are related to the safety function indicator criteria defined in SR-Can and also summarises the design premises in a table.

2 Design basis cases

2.1 General about design basis cases

2.1.1 Regulatory requirements

Regarding design basis cases in the safety assessment, the recommendations to the regulation SSMFS 2008:21 state the following: "*Based on scenarios that can be shown to be especially important from the standpoint of risk, a number of design basis cases should be identified. Together with other information, such as on manufacturing method and controllability, these cases should be used to substantiate the design basis such as requirements on barrier properties.*"

2.1.2 The role of the safety assessment

As stated in SSM's recommendations, the purpose of identifying design basis cases is to provide input to the formulation of requirements on barrier properties. This process is *iterative* and contains several elements:

1. Establishing of a repository design, i.e. a barrier system *with a chosen set of properties*, see Chapter 4 of the SR-Can Main report and the SR-Can Initial state report /SKB 2006e/.
2. Identification of the safety functions the system should fulfil over time, see Chapter 7 of the SR-Can Main report.
3. Identification of the external stresses the system will be subject to over time, potentially jeopardizing safety, summarised in Chapter 5 of the SR-Can Main report and further substantiated in the SR-Can Climate report /SKB 2006d, section 4.4.2/.
4. A quantitative analysis of how the identified external stresses affect safety for the established design. This analysis is provided in Chapters 9, 10 and 12 of the SR-Can Main report. The external load situations occurring in the scenarios that are particularly important from the standpoint of risk, i.e. a set of design basis cases, are briefly summarised below in this chapter. These provide important input to the formulation of the design premises.
5. Conclusions regarding the sufficiency of the chosen set of properties or recommendations regarding possible improvements. This is thus also important feedback to the design process.
6. The derivation of modified requirements on barrier properties based on step 5, leading to a modified design for which the above steps can be repeated.

For a particular safety assessment, a certain repository design, step 1, is hence provided. Steps 2, 3, 4 and 5 essentially constitute the safety assessment. Step 6 is, however, not formally within the scope of the safety assessment, see further section 2.1.5 'Integrated approach' below. An approach to setting safety related design premises on the barriers is thus needed as outlined in section 1.2. Chapter 3 and the summarising table in Chapter 4, show the result of applying this approach.

2.1.3 Scenarios

It is clear from the analyses in the SR-Can Main report that scenarios related to canister corrosion for an eroded buffer and to shear movements are most important from the standpoint of risk. As noted in the SR-Can Main report, the corrosion scenario is dependent on the extent to which buffer erosion takes place and this is an uncertain factor. In addition to these most important scenarios from the standpoint of risk, canister failure scenarios that did not contribute to risk, since the assumed design was sufficient to prevent failures, have also been considered among the design basis cases, although this is not a strict requirement in the nuclear safety regulations. The only such scenario identified in SR-Can is canister failures due to isostatic loads. Although such failures did not contribute to the calculated risk, the canister's resistance to isostatic loads is an important component of the design basis. Other scenarios than those leading to canister failures were not considered since such scenarios do, by definition, not cause any risk. However, the canister failure scenarios encompass a number of sub-scenarios relating to the buffer and to the host rock and these are thus included in the design basis cases.

2.1.4 Time scale

The design basis cases also depend on the time scale considered. For times longer than 100,000 years the recommendations to the regulation SSMFS 2008:37 states that: "*A strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with several supplementary indicators of the protective capability of the repository such as barrier functions, radionuclide fluxes and concentrations in the environment.*"

The likelihood that detrimental events like large earthquakes and major ice sheets would occur increases with time. The detrimental effects of some continuous processes, like canister corrosion, also increase with time. Following the recommendation, a strict application of the risk criterion is relevant in a 100,000 year time scale and since the design basis cases are to be derived from scenarios that are important from the standpoint of risk, this could be taken as an indication that also the design basis should be developed for this time frame. However, the principle of best available technique (BAT) applies over the one million year assessment time. It does not seem reasonable to develop the design premises for the timescale of 100,000 years and then use the one million year time scale when the principle of BAT is applied. Therefore, the one million year time scale will be considered also when the design premises are developed.

This does, however, not mean that the repository must be designed to withstand all loads identified in the safety assessment in a one million year perspective. The design must be such that the requirements on risk and BAT are met and this may well be compatible with the occurrence of some detrimental effects on the barriers during the assessment period.

2.1.5 Integrated approach

There is a considerable amount of information in SR-Can that can be used to further develop the design premises for a KBS-3 repository. There are, however, few, if any, load cases *on individual barriers* that can be directly derived from the external conditions alone. For example, the isostatic load on the canister will depend not only on the external conditions like the size of a future glacial load and associated groundwater pressure, but also on the depth of the repository and the design of the buffer, that determines its maximum swelling pressure. The situation regarding shear movements on the canister is even more complex: This depends on external factors like probabilities of future large earthquakes, but also on the fracture distribution at the deposition area, how the layout of the deposition area and deposition holes is adapted to the site conditions and the material properties of the buffer.

The load on one barrier will thus depend on the design of other barriers and on the site properties, meaning that the design premises must be determined for the entire barrier system in an integrated manner, and in some respects also site specifically. It also means that there is a range of different combinations of barrier and site properties that could provide a similar performance of the repository. The role of the safety assessment in this context is to provide input to the derivation of design premises, in the form of external loads the barrier system should sustain, informed by the calculated risk and, later, to audit the specific design and construction outcomes. It is, however, beyond the scope of the safety assessment report to develop the specific design. Safety assessment competence is though required for the appropriate formulation of the design premises.

The following is a summary of the most important results, *concerning the external loads the barrier system will be exposed to*, that need to be considered when the design premises are developed. It furthermore serves as an introduction to the more detailed discussion on feedback to canister and repository design in Chapter 3.

2.2 Canister; Isostatic load

The isostatic load on the canister depends on groundwater pressure and on the swelling pressure of the buffer. It is cautiously assumed that the sum of these two pressures determines the isostatic load. According to SR-Can Main report /SKB 2006a, section 4.2.8/ the saturated density interval of the buffer, 1,950–2,050 kg/m^3, corresponds to swelling pressures up to 13 MPa for MX-80.

However, a more rigorous handling of uncertainties in the estimate of swelling pressures suggests that the swelling pressure could be higher, up to 15 MPa.

The maximum isostatic pressure for the 100,000 year reference evolution were demonstrated to be 43 and 39 MPa, respectively, for the Forsmark and Laxemar sites, see SR-Can Main report /SKB 2006a, section 9.4.9, sub-heading 'Canister failure due to hydrostatic pressure'/. These maximum loads (sums of swelling pressure and hydrostatic pressure) are to be regarded as examples of what can be expected during a glacial cycle. Bounding estimates on maximum isostatic pressures indicate values up to 45 MPa, see SR-Can Main report /SKB 2006a, section 12.8.4/.

As discussed in SR-Can Main report /section 12.8.2 SKB 2006a/, global collapse is used as the criterion for canister failure as regards isostatic loads[2]. ("Global collapse" denotes a severe loss of structural integrity such that the canister's containment function can no longer be claimed. In contrast a, "local collapse" denotes a minor, local loss of structural integrity without consequences for the canister's containment function.)

In summary, if the canister is emplaced in a buffer with a density in the range 1,950–2,050 kg/m^3, corresponding to swelling pressures up to 15 MPa, the canister should withstand an isostatic load of 45 MPa. Thereby the global collapse due to isostatic load will remain a residual scenario, with no risk contribution.

From the standpoint of risk, it is important to realise that the isostatic loads mentioned above, at least the (dominating) contribution from the groundwater pressure at repository depth, is likely to affect *all canisters simultaneously*. If the canisters are not designed to sustain these loads, a substantial number of canisters could potentially fail simultaneously. This is different from cases where the natural variability of the host rock affects the load situation, e.g. as concerns the likelihood of a large fracture intersecting a deposition hole.

The canister may be subjected to asymmetric loads during different phases in the repository evolution. This could temporarily occur due to uneven water saturation in the buffer and lack of straightness of the deposition hole. Permanent asymmetric loads may occur due to an uneven buffer density distribution after water saturation in combination with lack of straightness of the deposition hole. Significant asymmetric loads are expected to be rare and thus to affect only a small fraction of the deposition positions. Such cases are useful for confirmation of the isostatic load case but have too low probability to be considered to coincide with the low probability shear load case discussed in the next section.

2.3 Canister; Shear movements

In rare cases, detrimental shear movements may occur as a consequence of earthquakes that could induce secondary movements in fractures intersecting a deposition hole. Shear movements will be analysed with the overall pressure due to swelling loads and water pressure. The response of the canister to these latter loads depends on a number of factors. The most important ones are:

- The magnitude and location of the earthquake.
- The length over which the intersecting fracture is sheared.
- The velocity of the fracture shear movement.
- The angle of intersection of the fracture and its position in relation to the main axis of the canister.
- The buffer mechanical properties, many of which depend strongly on the buffer density.
- The canister geometry and properties of the canister materials like Young's modulus and fracture toughness.
- The temperature of the canister and buffer at the time of the event.

[2] In SR-Can global collapse was denoted "total collapse".

The combined effect of all these factors determines if the canister will withstand a shear load. In SR-Can, this problem was analysed for the reference evolution, and further in the shear movement scenario, SR-Can Main report /section 12.9 SKB 2006a/.

The calculated mean number of canisters in unsuitable positions for 10 cm shear movements with a velocity of 1 m/s in case of a large earthquake was ≈0.5 out of 6,000 in the SR-Can assessment, SR-Can Main report /section 9.4.5 SKB 2006a/. Furthermore, due to the low probability of earthquakes, this corresponds to less than 0.12 failed canisters over 1,000,000 years. Additional analyses after the SR-Can assessment indicate that about 8 times as many canisters would be in unsuitable positions if 5 cm shear movements are to be avoided rather than 10 cm. The calculated risk is directly proportional to the number of canisters in unsuitable positions, and would thus increase eightfold for a 5 cm criterion (not taking credit for the fact that the buffer would be less impaired by a 5 cm movement).

Figure 2-1 shows the calculated risk due to shear movements in SR-Can (lines with dots). It is evident that the margin to the regulatory risk limit during the first 100,000 years, i.e. the time during which the risk limit applies, is considerable for both sites. An eightfold increase in risk would still give a substantial margin to the limit at 100,000 years (lines without dots). At one million years, the calculated risk would (just) exceed the limit for the Laxemar site, but not for the Forsmark site. This is acceptable according to applicable regulations. Furthermore, a large number of factors were pessimistically assessed in SR-Can, in particular such relating to the host rock when assessing the likelihood of detrimental shear movements. The calculation results are thus to be regarded as upper bounds.

Generally, the canister's resilience to a shear movement decreases with decreasing temperature. The analyses in the SR-Can assessment showed that extreme and unrealistic climate conditions are required to obtain temperatures below 0°C at a repository depth of 400 m, in a bedrock with a relatively high heat conductivity and neglecting the heat generated by the spent fuel in the repository. Therefore, temperatures below 0°C need not be considered for the shear case.

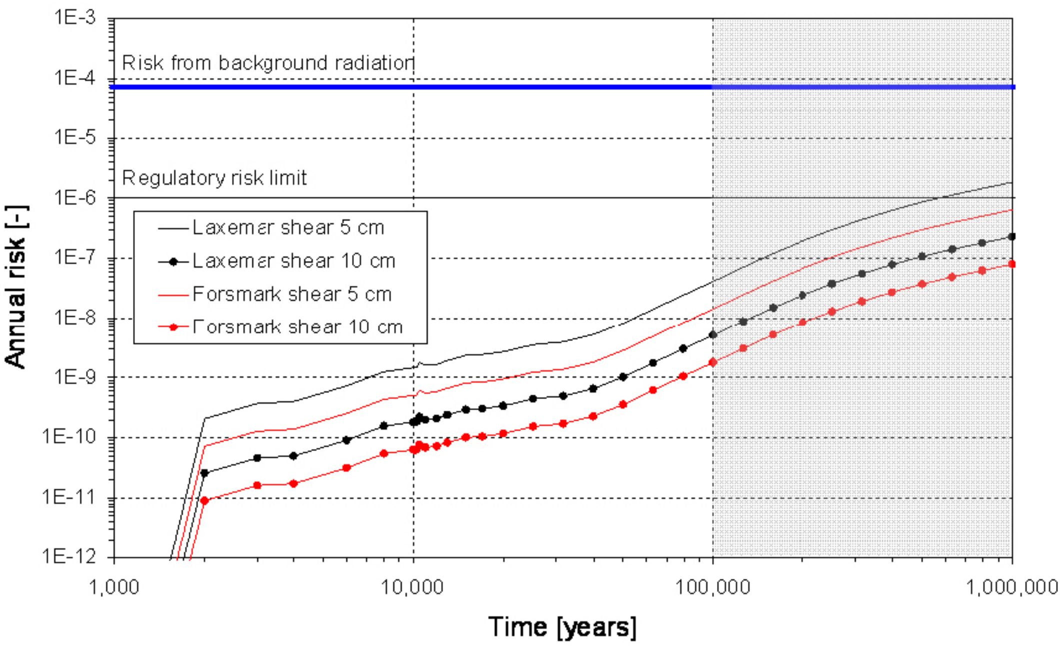

Figure 2-1. Calculated risk due to shear failure at Forsmark and Laxemar using SR-Can input data. In SR-Can it was assumed that a 10 cm shear movement is required to cause canister failure. The figure shows that also a 5 cm failure criterion would yield consequences that comply with the regulatory risk criterion with a margin. Repeated large shear movements at the same canister position are extremely unlikely and are not considered in the figure.

Based on these considerations, and in order not to place unduly strict requirements on the canister in relation to the overall risk contribution, the following design basis case is formulated:

- The copper corrosion barrier should remain intact after a 5 cm shear movement at 1 m/s for buffer material properties of a 2,050 kg/m^3 Ca-bentonite, for all locations and angles of the shearing fracture in the deposition hole and for temperatures down to 0°C. The insert should maintain its pressure-bearing properties to isostatic loads.

It is also noted that this risk contribution would dominate the total calculated risk if buffer erosion would be excluded as may be the case when further analyses of the buffer erosion process have been completed.

Furthermore, only few canisters would potentially be subject to shear movements of a detrimental magnitude if the repository is designed as outlined above. The majority of the canisters would be expected to experience only negligible shear movements since their deposition holes would be intersected by only small fractures, if any. It is thus only a small fraction of the deposition holes that are expected to have properties that require the canisters to withstand a 5 cm shear movement. To the extent that a distribution of shear movement resilience can be determined for the ensemble of canisters, taking into account e.g. manufacturing flaws, the potential part of the distribution not fulfilling the design requirements should be evaluated against the distribution of deposition hole properties in order to estimate the likelihood that a canister will experience shear failure.

2.4 Canister; Corrosion load

2.4.1 Introduction

One of the three long-term safety functions of the canister is to provide a corrosion barrier and a discussion of design basis cases as regards corrosion is, thus, required. The role of the safety assessment regarding corrosion loads is not merely to specify the load, but also to calculate the resulting corrosion depths. A more direct feedback can therefore be given in terms of the sufficiency of the canister thickness assumed in the safety assessment and sensitivities to variations in that thickness.

The corrosion loads on the canister depend critically on whether the buffer remains in the deposition hole to the extent that diffusive transport conditions prevail, or not. If the buffer fulfils its intended function as a barrier against advective transport, then it is concluded in SR-Can, as in several previous safety assessments, that a 5 cm copper thickness, with weld properties as assumed in the assessment, provides with margin a sufficient corrosion barrier over the one million year assessment period, see SR-Can Main report /sections 9.3.12, 9.4.9 and 12.7, SKB 2006a/.

The only identified situation in which corrosion could lead to penetration of the copper shell in SR-Can, is the one where the buffer is eroded, leading to advective conditions in the deposition hole. For the reference climate evolution, for the Forsmark site, between 5 to 60 per cent of all deposition holes would experience this condition depending on assumptions of flow model and spalling, SR-Can Main report /SKB 2006a, Figure 9-99/, and a pessimistic handling of the buffer erosion process. This increases the transport rate of sulphide from the groundwater and possibly also additional sulphide from sulphate reducing bacteria, the result being an enhanced corrosion rate.

It is uncertain if erosion of the buffer will occur to such an extent that advective conditions are created in the deposition hole. If this occurs, however, there are a number of additional uncertain factors that determine the resulting corrosion depths, such as the hydrogeological properties of the site over time and the concentrations and production rate of corroding agents, most notably sulphide, and factors limiting the activity of sulphate reducing bacteria (and rate (kinetics) for sulphide production).

2.4.2 Compliance with risk criterion

Pessimistic assumptions of both the extent of buffer erosion and of the factors influencing canister corrosion were used in the canister corrosion scenario in SR-Can, see SR-Can Main report /section 12.7 SKB 2006a/. The calculation result indicated close to 40 failed canisters at the Forsmark site and 120 at Laxemar over the one million year assessment period. The calculated risk consequences, conditional to the assumption that extensive buffer erosion occurs, were for both sites below the regulatory risk criterion for 100,000 years, i.e. in compliance with SSM's requirements. The calculated risk increases beyond 100,000 years, and becomes comparable to the background radiation for the least favourable site, Laxemar, after one million years, see Figure 2-2.

Based on the results in SR-Can, it is, therefore, concluded that a 5 cm copper thickness is sufficient for demonstrating compliance with the regulatory risk criterion, applicable for 100,000 years.

2.4.3 The one million year perspective

Regarding the entire one million year assessment period, it is appropriate to evaluate how an increased copper thickness would affect the calculated risk, in accordance with the requirements in the recommendations to SSMFS 2008:37 "*If the calculated risk exceeds the criterion of the regulations for individual risk…, the underlying causes of this should be reported on as well as possible measures to improve the protective capability of the repository.*" Therefore, the number of failed canisters during the one million year assessment period has been calculated for several canister thicknesses with otherwise the same pessimistic assumptions as for the canister corrosion scenario in SR-Can, see Figure 2-3.

The calculated risk at the end of the assessment period is approximately proportional to the number of failed canisters during the period. As seen in Figure 2-3, the number of failed canisters decreases slowly with increasing copper shell thickness, with all other conditions fixed. A doubling of the canister thickness to 10 cm would reduce the calculated number of failed canisters and thus the calculated risk at one million years by no more than about a factor of 2. This is confirmed in Figure 2-4 showing, for both sites, the risk associated with the corrosion scenario calculated for 5 and 10 cm copper coverage.

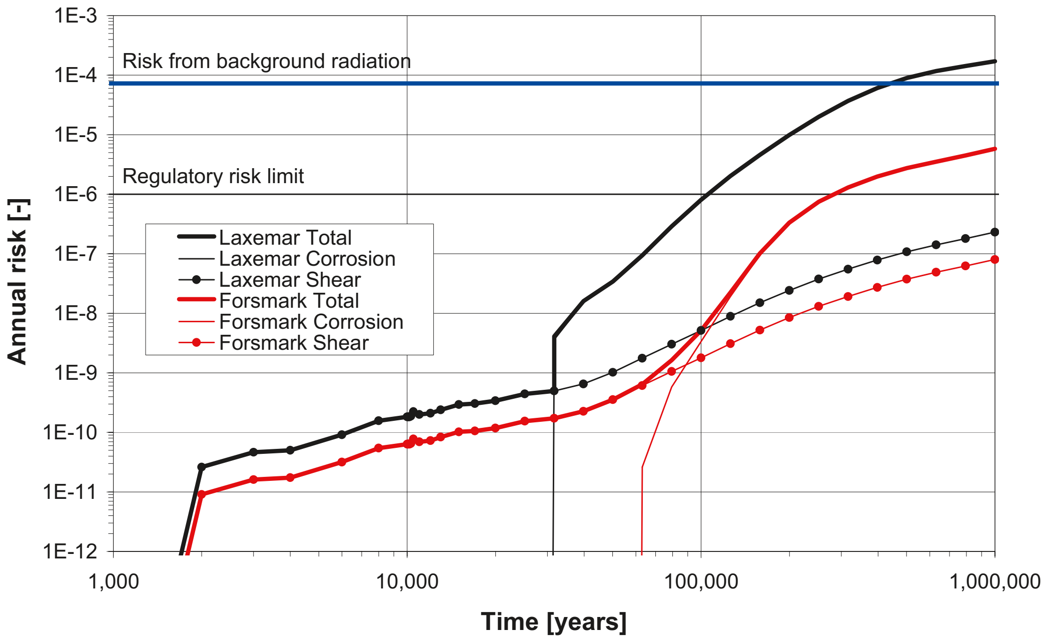

Figure 2-2. *Risk summation in SR-Can, expressed as annual individual risk for the two sites.*

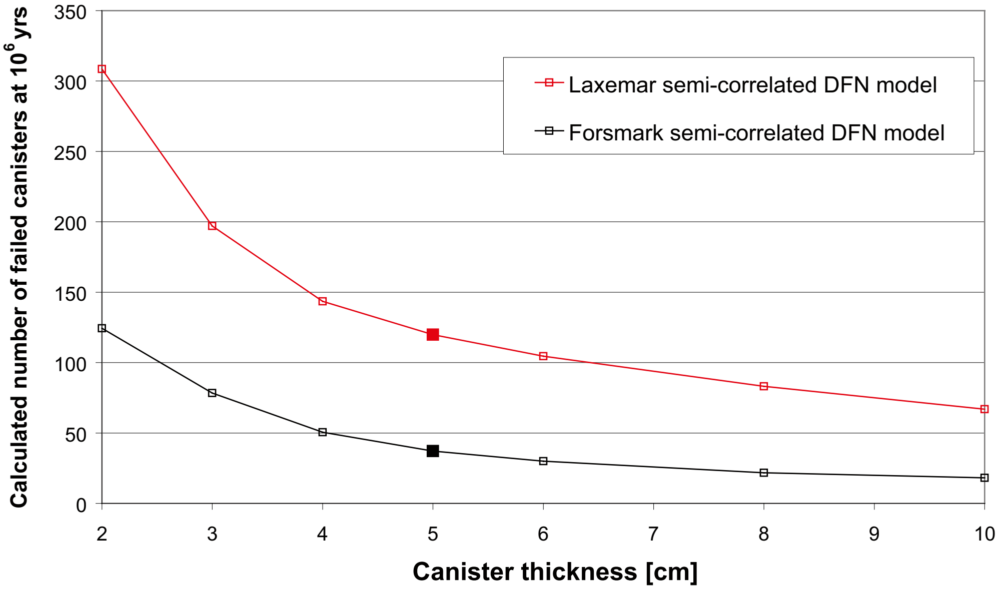

Figure 2-3. Calculated number of failed canisters after one million years as a function of canister thickness. All other assumptions as for the canister corrosion scenario in SR-Can, e.g. the analysis is based on 6,000 canisters.

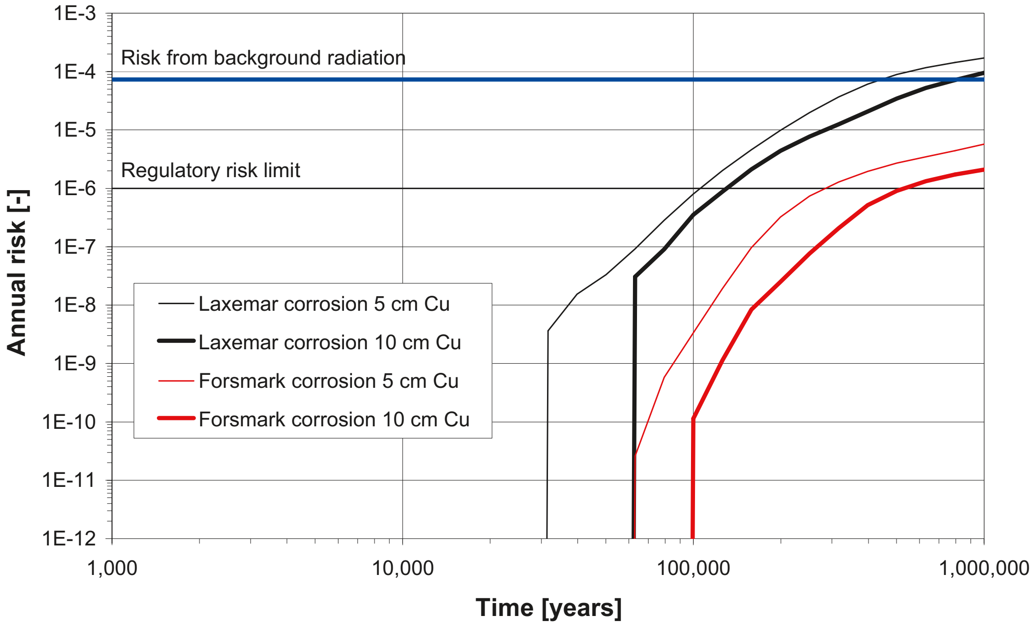

Figure 2-4. Comparison of risks associated with the corrosion scenario for 5 and 10 cm copper coverage using SR-Can data.

2.4.4 Conclusion

In summary, a strict design basis case for canister corrosion is not possible to derive due to the uncertain nature of the long-term processes involved. However, a 5 cm copper thickness was found sufficient to achieve compliance with the regulatory risk criterion in SR-Can. Furthermore, increasing the canister thickness would theoretically lead to fewer failed canisters during the one million year assessment period, but the reduction is moderate for e.g. a doubling of the thickness. Note also that no other potentially negative consequences, from a long term safety perspective, of an increased canister thickness like *i*) the possibility of handling the canister at all stages prior to deposition, *ii*) defect distribution when welding a different thickness, and *iii*) mechanical properties of the shell have been considered. Finally, it could also be noted, Figure 2-3, that a slight reduction of the copper thickness would only marginally increase the number of failed canisters and the risk. For example, reducing the copper thickness to 4 cm would imply 25% more failed canisters.

In conclusion, the copper thickness should be chosen so that the number of failed canisters due to corrosion does not exceed what is acceptable with respect to the risk criterion for 100,000 years. In SR-Can it was shown that 5 cm is sufficient for meeting the risk criterion. Thus a nominal thickness of 5 cm will be the required design premises for SR-Site. With respect to BAT an increased thickness adds very little reduced risk after 100,000 years in relation to other negative consequences on e.g. manufacturing and costs. Further increasing the copper thickness is thus not seen as motivated from a BAT perspective. Since the impact of corrosion is site and design specific it will be necessary to verify this in SR-Site, along with the safety related aspects of the BAT issue.

2.5 Buffer

The design basis cases, by definition, consist of descriptions of external loads a (particular component) of the repository may be exposed to during the one million year assessment period, with emphasis on scenarios of particular importance from the standpoint of risk. Such external loads for the buffer are listed below. They are based on a thorough understanding of the safety related functions of the buffer in the repository, i.e. on the role of the buffer in the safety concept. See further section 3.2 for a description of the role of the buffer in the repository. The buffer should be designed to withstand the load cases listed below.

The buffer may be exposed to chemical loads like dilute and saline groundwaters:

- Groundwaters with concentrations of divalent cations well below 1 mM over extended periods of time can not be ruled out, according to the analyses in SR-Can. It is presently unclear how the selected buffer materials respond to such chemical loads.
- Groundwaters with chloride concentrations up to around 1 M occur in the scenarios analysed in SR-Can. This poses no threat to the buffer functions.
- The buffer may also be exposed to pH loads up to pH 11 and this is acceptable according to the assessment in the SR-Can Buffer process report /SKB 2006b/. An initial, short term higher pH load cannot be excluded and should also be acceptable, based on mass balance arguments.

The buffer may also be exposed to isostatic pressures up to 33 MPa. The analyses in SR-Can show that the buffer materials analysed are not negatively affected by such pressures, see SR-Can Main report /section 9.4.8 SKB 2006a, sub-heading Liquefaction/.

Regarding shear movements, see the discussion of this issue for the canister above.

The function indicator criterion for buffer freezing was pessimistically assessed to be −5°C in SR-Can Main report /see Chapter 7, SKB 2006a/. The occurrence of buffer freezing depends on the site-specific thermal properties of the host rock, repository depth, heat production within the repository, and future climate conditions. The minimum temperatures calculated in SR-Can are −0.7°C at 400 m depth and +6.1°C at 500 m depth for the Forsmark and Laxemar sites, respectively. This is considerably higher than the buffer freezing temperature, which means that the −5°C criterion for the buffer material, is a workable design premise.

3 Safety related design premises

By applying the approach presented in section 1.2, it is possible to derive safety related design premises to the design of technical barriers and underground openings. The resulting design premises constitute fundamental input to the design. Designs that comply with the design premises form a good basis for demonstrating repository safety, according to the analyses in SR-Can. Some of the design premises may be modified in future stages of SKB's programme, as a result of analyses based on more detailed site data and a more developed understanding of processes of importance for long-term safety.

3.1 Canister

As discussed in Chapter 2, several design bases cases can be formulated for the canister. The design bases cases in turn, imply design premises on the other barriers.

3.1.1 Withstand isostatic load

Design premises

A barrier function of the complete canister (i.e. both copper shell and cast iron insert) is that it shall withstand isostatic load. The design basis case regarding isostatic load on the canister is described in section 2.2 as well as in SR-Can Main report /SKB 2006a, sections 13.4.1 and 13.4.2/. This design basis case leads to the following design premise:

- *The canister shall withstand an isostatic load of 45 MPa, being the sum of maximum swelling pressure and maximum groundwater pressure.*

Design implications for other barriers

This design premise is sufficient provided that:

- *The canister is surrounded by a buffer with a density less than 2,050 kg/m^3, corresponding to swelling pressures up to 15 MPa.*

These restrictions are thus a part of the design premises to be set on the tolerances on the buffer, see section 3.2.2.

3.1.2 Withstand shear load

Design premises

Another safety function of the canister is that it should withstand shear load. As justified in section 2.3 above, the design basis case is a 5 cm shear movement at 1 m/s with buffer as in SR-Can, i.e. with density < 2,050 kg/m^3. The design basis case is applicable to the canister as a whole (i.e. both copper shell and cast iron insert) as described in section 2.3. More background is found in SR-Can Main report /SKB 2006a, sections 13.4.2 and 13.5.1/. This design basis case leads to the following design premises:

- *The copper corrosion barrier should remain intact after a 5 cm shear movement at a velocity of 1 m/s for buffer material properties of a 2,050 kg/m^3 Ca-bentonite, for all locations and angles of the shearing fracture in the deposition hole, and for temperatures down to 0°C. The insert should maintain its pressure-bearing properties to isostatic loads.*

Design implications for other barriers

The design basis case builds on several assumptions on the state of the barrier and the deposition hole. This implies that the criterion above only is valid if the following restrictions apply:

- *Buffer: Buffer density < 2,050 kg/m³*
- *Geosphere: Deposition hole locations are selected in order to reduce the probability of large shear movements. In SR-Can this was achieved by applying the EFPC criterion /Munier 2006, 2007/.*

These restrictions are thus a part of the design premises to be set on the tolerances on the buffer, see section 3.2.2 and on the deposition hole, see section 3.3.1.

3.1.3 Withstand corrosion load

Design premises

Another safety function of the canister is to provide a corrosion barrier. As described in section 2.4 the copper thickness should be chosen so that the number of failed canisters due to corrosion does not exceed what is acceptable with respect to the risk criterion for 100,000 years. SR-Can Main report /SKB 2006a, section 13.4.2/ concludes that 5 cm of copper provides a considerable margin to avoid canister failures due to corrosion as long as the buffer is present and that 5 cm is sufficient to comply with the risk criterion at both sites if buffer erosion is as pessimistically handled as in SR-Can. The analyses of 5 cm copper thickness in SR-Can include uncertainties in copper coverage due to welding and non-destructive testing performance, see SR-Can Main report /SKB 2006a, section 9.4.9/. The design premise is

- *A nominal copper thickness of 5 cm, also considering the welds.*

As shown in section 2.4 an added thickness adds very little reduced risk after 100,000 years, and then other negative consequences on e.g. manufacturing and costs are not taken into account. Further increasing the copper thickness is thus not seen as motivated. However, since the impact of corrosion is site and design specific it will be necessary in SR-Site to verify that 5 cm is sufficient and re-address the safety related aspects of the BAT issue. In SKB's overall BAT argumentation, it is important to also consider negative implications of an increased thickness.

Design implications for other barriers

A prerequisite for the applicability of this design premise is that the buffer complies with the assumptions made in SR-Can, i.e. with a minimum density of 1,950 kg/m³, see further section 3.2. There are a number of additional uncertain factors that determine the resulting corrosion depths, such as the hydrogeological properties of the site over time and the concentrations and production rate of corroding agents, most notably sulphide, and factors limiting the activity of sulphate reducing bacteria and rate (kinetics) for sulphide production. Pessimistic assumptions of both the extent of buffer erosion and of the factors influencing canister corrosion were used in the canister corrosion scenario in SR-Can, see SR-Can Main report /section 12.7 SKB 2006a/.

3.1.4 Criticality

Design premises

SR-Can Main report /SKB 2006a, section 7.4/ states that

- *The spent fuel properties and geometrical arrangement in the canister should further be such that criticality is avoided even if water should enter a defective canister.*

This requirement is also in agreement with the general recommendations in SSMFS 2008:21.

Design implications for other barriers

For the fuel types analysed in SR-Can it was concluded, SR-Can Main report /SKB 2006a, section 10.3/ that the risk for criticality is negligible at a KBS-3 type repository in the Swedish bedrock. However, there are potentially criticality problems with low burn-up pressure water reactor (PWR) fuel. This raises the issue of how to handle odd fuel types, damaged fuel, etc. A strategy must be developed and these fuel types must be discussed in SR-Site.

3.1.5 Additional canister design premises

There are several additional design premises on the canister that can be derived from the safety assessment and in particular from the processes described in /SKB 2006c/. The considered processes are summarized in Table 3-1, with notes on the treatment in the safety assessment, and their role for the design of the canister.

Design premises

The following design premises are derived from Table 3-1:

- *To avoid gamma irradiation induced hardening and embrittlement of the cast iron material, the copper content in iron should be < 0.05%.*
- *The properties of the copper material are upheld providing the content of other elements are limited according to: phosphorus 30–100 ppm, sulphur < 12 ppm, hydrogen < 0.6 ppm and oxygen less than some tens of ppm. The grain size should be < 800 µm (average grain size).*
- *The amount of nitric acid formed within the insert is limited by changing the atmosphere in the insert from air to > 90% argon. The maximum amount of water left in the insert is set to 600 g.*
- *The hydrogen content in copper material < 0,6 ppm.*
- *The copper shell and the insert must not be exposed to temperatures substantially above 100°C. For higher temperatures (i.e. above 125°C) the materials need to be further assessed.*
- *The copper material should be highly pure copper to avoid corrosion coupled to grain boundaries. Oxygen contents of up to som tens of ppm can, be allowed.*
- *Corrosion due to formation of nitric acid is analysed and neglected for radiation in the order of 1 Gray/h.*

In addition cold work will change the creep properties of copper. Further experimental studies and modelling of effects from indentations and cold work are required to specify design premises.

Table 3-1. Processes of relevance for the canister, their treatment in the safety assessment, and their role for the design of the canister.

Origin of process	Feature/Process	Treatment in safety assessment SR-Can	Role for the design of the canister	Ref.
Radiation	Gamma irradiation induced hardening and embrittlement of cast iron.		Copper content in cast iron < 0.05%.	/Brissonneau et al. 2004/
	Radiation induced formation of nitric acid from nitrogen gas.	Outside canister: calculation of radiation and amount formed nitric acid (see below under Corrosion of copper).	Inside canister: change of atmosphere from air to > 90% argon, will limit the production of nitric acid. Analysed for maximum 600 g of water left in the insert.	/SKB 2006f, p. 23/
	Helium gas from radiation.	The pressure from formed helium gas is low compared to outer pressure.		/SKB 2006c, p. 66/

Origin of process	Feature/Process	Treatment in safety assessment SR-Can	Role for the design of the canister	Ref.
Thermal	Thermally induced changes in the material structure will change the mechanical properties.	Tensile tests and creep tests on copper have been performed at temperatures up to 100°C and 175°C respectively. Cast iron material according to standard EN-GJS-400-5U shows for this application negligible changes in material properties in the temperature interval 20–100°C.	The copper shell and the insert must not be exposed to temperatures substantially above 100°C. For higher temperatures (i.e. above 125°C) the materials need to be further assessed.	/SKB 2006f, p. 30/ /Andersson et al. 2007/
	Thermal conductivity.	The temperature is determined by other parts of the barriers than the canister material.		
	Thermal expansion coefficients of the copper shell and the cast iron insert.	Larger shrinking of the copper than the iron causes tensile stresses in the copper. These are neglected compared to the copper ductility.		/SKB 2006c, p. 85–86/
Hydrological	After canister failure water will intrude.	The coupled hydraulic and corrosion processes in the canister interior is handled by pessimistic estimates of: 1) the delay between the penetration of the copper shell and the onset of radionuclide transport, 2) the evolution of the hole size as a function of time.	The canister is designed to remain tight. No consideration is taken to water seeping into the interior of a leaking canister in the design.	/SKB 2006c, p. 38/
Mechanical	Macroscopic dicontinuities (scratches on the surface during handling etc) as a starting point for corrosion.	Initiation of localised corrosion occurs at the microscopic scale at grain boundaries, and will not be affected by the presence of macroscopic discontinuities. Discontinuities will not change the potential or the chemical environment, and the prerequisites for stress corrosion cracking is thus not enhanced.		/King 2004/
	Cold work introduced in the copper material during handling, transport etc.	Cold work will change creep properties of copper.	Further experimental studies and modelling of effects from indentations and cold work are required to specify design premises.	
	Creep ductility.	Phosphorus added for sufficiently high creep ductility.	Grain size < 800 µm (measured as average grain size). Phosphorus content 30–100 ppm. Sulphur content < 12 ppm.	/Andersson et al. 1999/
Chemical	Embrittlement of copper.	Hydrogen gas may cause embrittlement during manufacturing process.	Hydrogen content in copper material: < 0,6 ppm.	/Dies 1967/

Origin of process	Feature/Process	Treatment in safety assessment SR-Can	Role for the design of the canister	Ref.
	Chemical compostion of the copper material will influcende the mechanical properties.		The material used for trial production and testing has had the requirement < 5 ppm oxygen, in accordance to the chosen standard, For a change of the material further testing is needed.	
	Corrosion of insert.	Nitric acid formed from radiolysis of nitrogen gas can cause general corrosion and stress corrosion cracking of the cast iron. After failure of copper shell: – Generation of hydrogen gas. – Formation of corrosion products. Time from a small hole to a larger hole is included in the radionuclide transport calculations.	Change of atmosphere to argon insert the insert gives negligable amounts of nitiric acid (see above). After failure the canister is not designed to withstand specified loads.	/SKB 2006c, section 3.5.1–3.5.3/
	Corrosion of copper.	The conclusion that if the buffer fulfils its intended function as a barrier against advective transport, then a 5 cm copper thickness provides with margin a sufficient corrosion barrier over the one million year assessment period, is based on that processes are treated either: – as having no or very small influence on canister life time (stress corrosion cracking, corrosion due to high chloride concentration, corrosion due to earth currents, deposition of salt on the copper surface), or – with quantitative evaluation of processes by mass balance considerations and by calculations on corrosion determined by diffusive and advective transport.	Section 2.4 gives the Design bases case for copper thickness. The analyses of corrosion are made on copper material specified from other requirements, including specifications according to used standards. The copper material should be a highly pure copper to avoid corrosion coupled to grain boundaries. Oxygen contents of up to som tens of ppm can, however, be allowed. Salt deposition is neglected if temperature on the canister is in the order of 100°C. Corrosion due to formation of nitric acid is analysed and neglected for radiation in the order of 1 Gray/h. The prerequisites for stress corrosion cracking (potential, agents, tensile stresses) will not, if at all, be present simultaneously during sufficient times. The quantitative evaluations are performed for groundwater chemistry typical in Swedish granitic bedrock and for bentonite pore water. Concentration of sulphide is assumed to be < 5×10^{-5} mol/l.	/SKB 2006c, section 3.5.4–3.5.7/ /King et al. 2001/ /Gubner et al. 2006/ /Gubner and Andersson 2007/

3.2 Buffer

3.2.1 Buffer material – long-term durability

One outcome from SR-Can was that the long-term performance of the buffer depends critically on the extent to which colloid release will occur. As demonstrated in the analyses presented in the SR-Can Main report, colloid release could jeopardise practically all buffer safety functions. There are, however, large uncertainties associated with the assessment of the extent of the release process and further knowledge could either confirm the problematic nature of this process or lead to the conclusion that it can be neglected.

If colloid release can be shown to be limited, then, based on the analyses carried out in SR-Can, both the buffer materials, MX-80 and Deponit CA-N, are expected to fulfil all function indicators over the assessment period. There are however some differences that should be noted.

- Swelling properties: Both materials have roughly the same swelling properties at the design density, although the swelling pressure and shear strength is higher for Deponit CA-N.
- Hydraulic conductivity: Both materials have roughly the same hydraulic properties at the design density. The changes in behaviour at lower densities are the same as for the swelling pressure.
- Piping properties: Both materials are sensitive to piping and erosion during the saturation phase.
- Colloid release properties: Deponit CA-N has a high content of divalent cations in ion exchange positions and due to its content of calcite and dolomite. This could potentially be a benefit for avoiding colloid release. However, the long-term effect of this is uncertain.
- Impurities: Deponit CA-N has a higher content of pyrite, which may corrode the canister. The total effect of this is relatively small. The maximum allowed content, see section 3.2.4, will be specified at purchase if this material should be selected. The organic content of the bentonite may also contribute to canister corrosion, at least if microbes are active. The investigations in SR-Can showed that both materials were equal in this respect.
- Freezing properties: The difference in freezing properties has not been evaluated. The basis for the freezing evaluation in SR-Can was the mineral (montmorillonite) surface area, which should be about equal for both materials.

The buffer materials will also react differently to the chemical environment in the repository, SR-Can Main report /sections 4.2.8 and 9.4.8 in SKB 2006a/.

Both the reference materials are from major bentonite suppliers. The quality control on the suppliers' side can be expected to be equal. SKB will assess the quality assurance of the suppliers and will check that the buffer material meets specifications on delivery.

With the exception of the colloid release process, the conclusion is that both materials will fulfil the function indicators, and the differences between them in a performance perspective are too small to make any ranking possible. Further studies of the colloid release process may, however, lead to a different conclusion in this respect.

It is important to note that material selection is only one part of making an adequate buffer. It is also important to have adequate quality control for the delivered material, and for manufacture and emplacement of the buffer blocks.

Design premises

As further outlined in section 2.5 and in SR-Can Main report /SKB 2006a, section 13.4.2/, a design basis case for the long term durability of the buffer material is that the buffer may be exposed to a range of conditions. The buffer materials considered for SR-Can maintained their safety functions for these conditions, except regarding the stability against colloid release in case groundwater concentrations of divalent cations stay below 1 mM. It is presently unclear how the selected buffer materials respond to such chemical loads, but SR-Can could demonstrate safety even if it was assumed that the buffer was unstable below this concentration. It is consequently set as a design premises that:

- *After swelling the buffer should uphold the minimum swelling pressure 2 MPa and the hydraulic conductivity should not exceed 10^{-12} m/s independently of dominating cation and for chloride concentrations up to 1 M. After swelling the shear strength of the buffer must not exceed the strength used in the verifying analysis of the canisters resistance against shear loads. These conditions apply for temperatures down to 0°C and temperatures up to 100°C.*

Additional requirements on the buffer material are provided in section 3.2.4.

Design implications for other barriers

The list of conditions implies several restrictions on the other barriers:

- The chemical requirements and the minimum temperature requirement, concern site specific conditions, and thus affects the selection of acceptable repository volumes and depths, see further section 3.4.5. Furthermore, while it is expected that the buffer may be exposed to extended periods of groundwater concentrations of divalent cations below 1 mM, it is clearly a benefit if the groundwater concentration exceeds 1mM in order to avoid colloid release from buffer and backfill, see SR-Can Main report /SKB 2006a, section 7.3.4/.
- As also pointed out in SR-Can Main report /SKB 2006a, section 7.3.4/, groundwaters of high ionic strengths would have a negative impact on the buffer and backfill properties, in particular on the backfill swelling pressure and hydraulic conductivity. In general, ionic strengths corresponding to NaCl concentrations of approximately 70 g/l (1.2 M NaCl) are a safe limit for maintaining backfill properties whereas the corresponding limit for the buffer is around 100 g/l (1.7 M NaCl). The limit of tolerable ionic strength is however highly dependent on the material properties of these components, /SKB 2006a, section 4.2.8/ and since, in particular for the backfill, alternative materials are to be evaluated in the assessment, no specific criterion is given here.
- The maximum temperature requirement concerns the repository layout and design in relation to the site properties, see further section 3.3.4.

3.2.2 Initially deposited buffer mass

Design premises

As described in SR-Can Main report /section 7.3.2 SKB 2006a/, there are several requirements concerning the minimum buffer swelling pressure, which in turn can be transferred to conditions on the minimum saturated buffer density. In short these conditions concern:

- *Limiting advective transport.* A guideline is that the hydraulic conductivity of the buffer should fulfil /SKB 2006b, section 2.5.2/: $K_{Buff} < 10^{-12}$ m/s. The hydraulic conductivity is strongly related to the density of the buffer, to the adsorbed ionic species and to the ionic strength of the surrounding groundwater. An additional requirement for the limitation of advective transport is that the swelling pressure should exceed 1 MPa in order to ensure self-sealing and homogeneity of the buffer /SKB 2006b, section 2.4.1/. The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled, also when the initial, expected swelling of the buffer towards the deposition tunnel has occurred, and after local erosion of buffer during the saturation phase.
- *Eliminate microbes*. The buffer should have a sufficient swelling pressure to prevent bacteria from surviving in it. Based on the assessment of microbial activity presented in /SKB 2006b, section 2.5.13/, SR-Can Main report /SKB 2006a, section 7.3.2/ established that this will occur at swelling pressures exceeding 2 MPa. Such swelling pressures occur for densities above 1,900 kg/m^3. With an additional margin to account for losses due to piping erosion, this leads to the requirement that the saturated density must exceed 1,950 kg/m^3. This is, however, still subject to studies and future results will show if this criterion can be further substantiated.
- *Prevent colloid transport through buffer.* The diffusive transport of fuel colloids through highly-compacted bentonite is, assumed to be negligible, due to the tortuosity and small size of the bentonite pores. Experiments with 1 nm gold colloids show that the microstructure of a bentonite with a dry density of 1,000 kg/m^3 effectively filters gold colloids. This corresponds to a saturated clay density of about 1,640 kg/m^3. Even at these densities colloids will diffuse through the bentonite, but the transport capacity is limited. The judgement is that the colloid transport in the buffer can be neglected if the density at saturation exceeds 1,650 kg/m^3.

- *Keep the canister in position.* Also, the swelling pressure should be sufficient to prevent the canister from sinking in the deposition hole since this would render the canister in direct contact with the rock thus short-circuiting the buffer. Calculations made for SR-Can /Börgesson and Hernelind 2006/ of canister sinking in a deposition hole for a range of buffer densities and hence swelling pressures indicate that the sinking will be less than 2 cm for swelling pressures down to 0.1 MPa, see further /SKB 2006b, section 2.4.1/. Based on these calculations, SR-Can selected 0.2 MPa as a cautiously formulated safety function indicator criterion.

As can be seen the most strict of the above criteria concern prevention of microbial activity, i.e. as long as the swelling pressure exceeds 2MPa the other safety functions are automatically upheld. Furthermore, SR-Can Main report /SKB 2006a, section 9.4.10/ concludes that for deposition holes with reference buffer density, the swelling pressure criterion is fulfilled with ample margin, also for groundwater salinities that can be expected during the reference glacial cycle. For a deposition hole that has experienced loss of buffer mass due to erosion/colloid release and to the extent that advective conditions prevail, the swelling pressure requirement can, however, not be guaranteed. This means that an initial buffer density leading to saturated densities > 1,950 kg/m^3 is adequate for a sufficient swelling pressure, with margin to a moderate loss due to piping erosion.

There is also a requirement on the maximum shear strength of the buffer. This requirement can be expressed as maximum buffer density. The condition set out in section 3.1.2 for the canister withstanding shear load, requires that the saturated buffer density is less than 2,050 kg/m^3.

In conclusion, the initially deposited buffer mass should be such that it corresponds to a saturated buffer density in the volume initially filled with buffer that is:

- *less than 2,050 kg/m^3 to prevent too high shear impact on canister (see 3.1.2), and*
- *higher than 1,950 kg/m^3, i.e. sufficiently high to ensure a swelling pressure of 2MPa with margin for possible loss of material.*

If these premises are met, the long-term requirements on hydraulic conductivity, swelling pressure etc mentioned above are likely to also be met in all parts of the buffer also after the initial swelling and upward expansion toward the deposition tunnel backfill, but this must be verified in the safety assessment SR-Site.

Design implications for other barriers

For given buffer material and pre compaction, this condition implies:

- restrictions on deposition hole geometry, see section 3.3.5,
- requirements regarding the water inflow into the deposition hole in order to restrict piping erosion during water saturation, see section 3.3.2, and
- restrictions on the compressibility of the tunnel backfill, see section 3.4.1.

3.2.3 Buffer thickness

The main risk contribution for the time period beyond 100,000 years is strongly linked to the long-term evolution of the buffer and in particular the extent of colloid formation/erosion for intrusion of glacial melt water. This situation cannot be excluded for extended periods of time during a glacial cycle. Knowledge of the buffer colloid formation/erosion process is limited. A crude model has been used to assess the extent of this process. Better knowledge could lead to both higher and lower estimates of this extent. It is, however, important to note that a higher extent would have a very limited impact on the consequences reported since, if buffer erosion occurs to such a degree that advective conditions are created in the buffer, then it is the 50 mm copper canister thickness that determines the time required for canister failure with the model used in the SR-Can assessment. However, it is possible that a better understanding of the process would allow neglect of buffer erosion in future assessments.

Relating to the issue of BAT, the results from SR-Can indicate that a thicker buffer would only improve the situation marginally. The time required to create advective conditions in the buffer would increase with the increased buffer mass loss required to create such conditions, but this time is overshadowed by the considerably longer time required to corrode the canister to the extent that a failure occurs. It is thus concluded that an increased buffer thickness would not improve the situation markedly. The main route for handling the issue of buffer erosion/colloid release appears to be an increased knowledge of the nature of the erosion process, so that better founded assessments of its potential occurrence and extent can be made in future assessments. It may also be possible to solve the issue by engineering measures. However, at present, no designs that may resolve the problem with colloid formation in a satisfactory way have been suggested.

An increased buffer thickness will reduce the damage on the canister at a rock shear, but given the high shear stiffness of highly compacted bentonite, the effect is marginal. An increased buffer thickness will also increase the overall buffer mass, which would make the buffer more resistant to alteration and mass-loss processes (i.e. a smaller fraction of the total mass will be altered/lost). Still, it is not an unambiguous advantage since an increased thickness also would decrease the heat transfer capacity. An increased diameter would also increase the diffusional distance between the canister and the rock. However, this would also lead to a bigger deposition hole, which would increase the probability of intersection of a water conductive fracture.

Design premise

As a design premise:

- *the buffer dimensions used as reference dimensions in SR-Can shall be used, in addition to other requirements affecting the buffer and deposition hole geometry, in particular as stated by sections 3.2.2 and 3.3.5.*

Change of dimensions has implications on fulfilling requirements on the canister and on the fulfilment of thermal requirements and are not judged worthwhile.

Design implications for other barriers

Buffer thickness is the difference between canister and deposition hole radii and need thus be selected in combinations with these. Change of radius will also affect the design basis cases for the canister.

3.2.4 Mineralogical composition of buffer material

From a safety assessment point of view there are two basic mineralogical criteria that always have to be fulfilled concerning the buffer material. Firstly, the montmorillonite content has to be sufficiently high, and secondly, the content of harmful accessory minerals has to be sufficiently low /SKB 2006b, section 2.5.6/.

Design premises

The buffer density interval stated in the design premises, section 3.2.2, is based on a montmorillonite content of 75 to 90 per cent for the dry material. The specified densities are not valid outside this interval. High grade commercial bentonite normally contains more than 75% montmorillonite by weight for the dry material. Additional demands on the total layer charge and the layer charge distribution will likely be used, but the limits are not presently defined.

Since the bentonite buffer is a natural material, a mineralogical variation with respect to accessory minerals must be accepted. None of the present accessory minerals in the bentonites studied in SR-Can have any identified importance for the function, as long as the montmorillonite content is above 75% as stated above. Nevertheless, SKB's currently considered practice is to only accept a variation of ± 50%, or ± 1 wt-% for material of low content, of the given reference value for each single mineral, provided that the basic montmorillonite criterion is still fulfilled.

Only sulphides and organic carbon are considered possibly harmful in the present reference bentonites. Special criteria will therefore be used for these substances both with respect to accepted contents and to analyzing methods. Similar treatment will be used in case of other potentially harmful substances in the bentonite. The content of organic carbon should be less than 1 wt-%. The sulphide content should not exceed 0.5 weight percent of the total mass, corresponding to approximately 1% of pyrite. Furthermore, there is also reason to put a limit on the sulphate content, since sulphate could be reduced to sulphide. A limit of 1 wt-% of the total sulphur content should be applied.

In summary, the following design premises apply for the dry buffer material:

- *The montmorillonite content of the dry buffer material shall be 75–90% by weight.*
- *The content of organic carbon should be less than 1 wt-%*
- *The sulphide content should not exceed 0.5 weight percent of the total mass, corresponding to approximately 1% of pyrite.*
- *The total sulphur content (including the sulphide) should not exceed 1 wt-%.*

3.2.5 Non-dimensioning buffer design requirements

There are a few additional design requirements on the buffer that can be derived from SR-Can. These concern canister corroding agents, liquefaction and gas transport. However, given that the above design premises are upheld, these requirements will be also be upheld. They are nevertheless listed here, e.g. to ensure that they are considered in case there is a revision of the other design premises. The requirements are fulfilled for both buffer materials used in SR-Can (MX-80 and Deponite CA-N) within the density spans given by the requirements in section 3.2.2 and for the mineralogical requirements in section 3.2.4.

Canister corroding agents

The buffer material should not contain canister corroding agents. This is covered by section 3.2.4.

Liquefaction

Liquefaction is a process implying that a stiff granular material suddenly turns into liquid due to a short duration impact. According to /SKB 2006b, section 2.4.2/ liquefaction may occur either due to a very high water pressure or a convergence of the deposition hole resulting in a very high water pressure. However the required water pressure is higher than could be expected under any currently recognized scenario and the expected maximal stress increase in the rock and convergence of the deposition hole are clearly lower than required for liquefaction to appear. The process was therefore not considered within the SR-Can study and there is consequently no reason to formulate design premises relating to liquefaction.

Admit gas transport through the buffer

If a canister should be defective such that water could penetrate through the copper shell, the cast iron insert is expected to corrode, resulting in hydrogen gas formation.

If the production rate is higher or the gas quantity is larger than can be removed via dissolution and diffusive processes, a gas phase will form, the pressure will rise, and a flow path is expected to be formed through the buffer at a critical pressure, see /SKB 2006b, section 2.3.3/.

Available experimental results show that gas can migrate through a highly compacted buffer without jeopardizing the continued function of the buffer.

3.3 Deposition holes

3.3.1 Provide mechanically stable conditions

As discussed in SR-Can Main report /SKB 2006a, section 9.4.5/, one of three identified failure modes of the canister is that due to a rock shear movement across a deposition hole. An integrated evaluation of the response of the buffer and canister to rock shear has lead to a need to reject deposition holes in order to reduce the probability of large shear movements, see sections 2.3 and 3.1.2 above. The magnitudes of shear movements due to earthquakes, and how the shear movement relates to the position of deposition holes, is discussed in /Munier and Hökmark 2004/.

The main conclusion is that if the canister is positioned beyond a respect distance from a deformation zone that could host a major earthquake, and the canister is not intersected by large fractures, earthquakes in the vicinity of the repository will not affect canister integrity. Deformation zones capable of hosting major earthquakes must have a surface trace length exceeding 3 km or an equivalent area for gently dipping zones that lack any surface intersection. In SR-Can such fractures where those considered to have a potential for shearing > 10 cm and it was demonstrated that this could concern fractures having radii exceeding 75 m if centred between 100 m and 200 m from deformation zones potentially capable of hosting large earthqueakes and 150 m if centred farther than 200 m from such zones /Munier and Hökmark 2004, Fälth and Hökmark 2006/.

The repository design assessed in SR-Can placed deposition areas with a respect distance of 100 m to deformation zones with trace lengths exceeding 3 km. Means to avoid fractures with radii larger than 75 m and 150 m, respectively, were searched for. Application of the full perimeter intersection criterion (FPC) results in a high efficiency in reducing the number of deposition holes intersected by large fractures at the expense of a moderate increase in total deposition tunnel length. To further increase the efficiency, also fractures intersecting several deposition holes, without intersecting the tunnel, the so called extended FPC criterion, EFPC, /Munier 2006, 2007/ was considered. It is an expert opinion /Cosgrove et al. 2006/ that identification of these remaining long fractures in the deposition holes is fully possible, but that the specific criteria to apply would be site specific and can only be fully established by the detailed investigations that are possible to carry out during the construction phase. Furthermore, such geological/geophysical criteria would be correlated with criteria for avoiding high flow rates.

Additional analyses after the SR-Can assessment, see section 2.3, indicate that about 8 times as many canisters would be in unsuitable positions, by applying the EFPC, if 5 cm shear movements are to be avoided rather than 10 cm. As discussed in section 2.3, this increase is acceptable and EFPC is thus a sufficient design premises even if 5 cm shear would lead to canister failure. Furthermore, additional studies are warranted for devising efficient means of applying the EFPC criterion, although the final specification of the approach to be adopted could only be established detailed investigations during the construction phase. It should also be noted that it may be possible to reduce the respect distance of 100 m to some deformation zones based on an a site specific detailed and individual assessment of their properties combined with revised criteria for what fractures should be avoided in deposition holes.

Design premises

The following design premises apply:

- *Deposition holes are not allowed to be placed closer than 100 m to deformation zones with trace length longer than 3 km.*
- *Deposition holes should, as far as reasonably possible, be selected such that they do not have potential for shear larger than the canister can withstand. To achieve this, the EFPC criterion should be applied in selecting deposition hole positions.*

These rules may be adjusted for the detailed design, as suggested in the above section.

Design implications for other barriers

For the given design premises on the canister and buffer there are no implications for the other barriers. However, in case there was a need to change the criteria on mechanical stability of deposition holes, this would strongly affect the conditions for the canister.

3.3.2 Provide favourable hydrologic and transport conditions

As discussed in SR-Can Main report /SKB 2006a, section 13.6.4/, large fractures and fractures with high flow rates intersecting deposition holes are common factors for many identified safety related issues. Flow in fractures intersecting deposition holes affects:

- piping and erosion during the water saturation phase,
- colloid release,
- effects of oxygen penetration,
- inflow of corrodants, potentially leading to canister failure, and
- outflow of radionuclides (in both cases in particular for eroded buffer).

The flow rate depends on the transmissivity of the intersecting fractures and how these fractures are connected with the fracture network. This means that there is generally a correlation between high flow rate and fracture size since long fractures have a much higher probability to be connected and since fracture transmissivity is likely correlated to fracture size, although the extent of this correlation is uncertain.

Applying the FPC criterion, as well as a criterion related to intersecting fracture transmissivity, is highly efficient in reducing the number of deposition holes with high flow rate, but this efficiency reduces dramatically for DFN-model variants with less correlation between fracture size and transmissivity. Furthermore, a simple transmissivity criterion would then also unnecessarily reject a large number of deposition holes with very low flow, just because they were intersected by very short highly transmissive fractures. If this very short, but highly transmissive, fracture is connected to much less transmissive fractures both the inflow and the saturated flow will be quite small.

In contrast, there is likely to be a strong correlation between the inflow to open deposition holes and flow conditions during saturated conditions. This is also confirmed by preliminary analyses by /Svensson 2006/. High flow rates around deposition holes after saturation are also generally associated with low transport resistance (so called F-values) in the geosphere. Consequently, avoiding deposition holes with too high inflow will also reduce the number of deposition holes with unsuitably high flows during saturated conditions.

Design premises

In order to mitigate piping/erosion SR-Can Main report /SKB 2006a, section 9.2.4/ considered a maximum allowed inflow of 0.1 L/min to open deposition holes. However, subsequent analyses /Åkesson et al. 2010/ suggests that this criterion was not sufficient and instead relates the amount of erosion to the amount of water passing the deposition hole during saturation. The following criterion is suggested:

- *The total volume of water flowing into a deposition hole, for the time between when the buffer is exposed to inflowing water and saturation, should be limited to ensure that no more than 100 kg of the initially deposited buffer material is lost due to piping/erosion. This implies, according to the present knowledge, that this total volume of water flowing into an accepted deposition hole must be less than 150 m^3.*

It should be noted that there may be various approaches for meeting this criterion. One approach may be to reject potential deposition holes with too high inflow in relation to the total inflow to the tunnel (including the total inflow into deposition holes), but various engineering approaches, including grouting of deposition holes or artificial wetting of the tunnel, which would decrease the saturation time, may possibly be considered – as long as these actions are compatible with the design premises.

With regard to the safety functions affected by high flows during saturated conditions, see the bullet points in the introduction to this section, the following applies:

- *Fractures intersecting the deposition holes should have sufficiently low connected transmissivity.*

This condition is most likely fulfilled if the conditions regarding inflow to deposition holes are fulfilled, but a more practically applicable criterion is needed. This can only be done within the context of a full safety assessment, i.e. this needs to be assessed in SR-Site. The following matters need to be considered:

- The long-term stability of the measured transmissivity needs to be considered. Possibly a robust criterion would need not only to consider currently measured transmissivity (or flow), but also evidence of high flow in the past. /Cosgrove et al. 2006/ point out that if fractures of large magnitude have experienced high flows in the past, this would result in the walls of the fractures having been altered either physically or chemically and/or minerals having been deposited along the fractures. Such features are easily identified from tunnels by direct observation and can be detected in boreholes using geophysical techniques. This could provide an additional, important criterion for identifying large fractures.
- The criterion needs to be tested, at least theoretically, in a numerical discrete fracture network (DFN) model exploring its implications for different assumptions on the correlation of flow with fracture size. Such analyses could build on the preliminary analyses by /Svensson 2006/ discussed above.
- Its practical applicability needs also be considered, including assessment of "skin-effects" and the effects of potential disturbances from grouting before measurements are conducted.

It is emphasised that the flow rate criterion will not be independent of the fracture size criterion, especially when there is a strong correlation between fracture size and transmissivity. As already noted, the FPC criterion alone is quite effective in removing high flow rate deposition holes for the fully correlated case, and application of the EFPC criterion should improve this effectiveness. Furthermore, /Cosgrove et al. 2006/ point out that there is generally a correlation between fracture size and evidence of strong fluid movement. When estimating the degree-of-utilisation, the correlation between the criteria should be considered, in order not to be overly pessimistic about the required space.

Design implications for other barriers

The inflow criteria during unsaturated conditions are related to the requirements for avoiding piping/erosion. Since the volume of inflow also depends on the backfill and plugging, this cannot be interpreted as a requirement on the deposition hole alone. Also if the buffer/backfilling design is changed these requirements need to be reconsidered.

3.3.3 Provide favourable chemical conditions

Design premises

As discussed in SR-Can Main report /SKB 2006a, section 7.5 (Figure 7.2)/ and following the conditions expected for the buffer, see section 3.2.1, the groundwater composition in rock volumes selected for deposition holes should, prior to excavation, fulfil the SR-Can function indicator criterion R1 on favourable chemical conditions. This function indicator criterion, which should also be seen as a design premises states:

- *Reducing conditions*
- *Salinity; TDS limited*
- *Ionic strength; $[M2+] > 1$ mM*
- *Concentrations of K, HS^-, Fe; limited*
- *pH; $pH < 11$*
- *Avoid chloride corrosion; $pH > 4$ or $[Cl^-] < 3M$.*

When quantitative criteria could not be given, the term "limited" was used to indicate favourable values of the safety function indicators. The requirements concern conditions prior to excavation, whereas SR-Site would need to verify that the long term evolution of these conditions still result in a safe repository. The conditions could not a priori be expected to be fulfilled for all times in the future.

Design implications for other barriers

These geochemical conditions are assured by selection of appropriate repository volumes and depth, see section 3.4.5. These conditions cannot be checked for individual deposition holes since the water composition there will be temporarily disturbed. Justification of suitability for selected deposition areas is given in the Site engineering report (SER) and should be confirmed in SR-Site.

The groundwater composition is also influenced by the chemical interaction with the buffer porewater having design implication on the buffer mineralogical composition. This is covered by section 3.2.4.

3.3.4 Provide thermally favourable conditions

Design premises

As concluded in SR-Can Main report /SKB 2006a, section 13.6.7/ the following design premises, expressed as a thermal requirements on the buffer (see section 3.2.1) can be set:

- *The buffer geometry (e.g. void spaces), buffer water content and distances between deposition holes should be selected such that the temperature in the buffer is < 100°C.*

Design implications on other barriers

Since the buffer geometry and canister heat output is selected for other reasons, this criterion essentially concerns the adaptation to site properties by selecting the spacing of deposition holes and the repository depth. The principles of the thermal dimensioning are found in /Hökmark et al. 2009/. It is based on reference design values for total decay power of encapsulated fuel elements, thermal properties and geometry of the buffer, thermal properties and geometry of the backfill and geometry of deposition holes and tunnels. If the reference design is changed, this would also require changing the thermal design.

3.3.5 Accepted tolerances and disturbances prior to emplacement

Design premises

SR-Can did not assess the impact of an excavation damaged zone (EDZ) along the deposition hole. However, subsequent analyses /Joyce et al. 2008/ indicate that such a zone would have negligible impact even if there is an EDZ , with $T=10^{-9}$ m^2/s, surrounding and along the deposition hole wall. Based on this if the following, possibly too strict, condition may be formulated:

- *Before canister emplacement, the connected effective transmissivity integrated along the full length of the deposition hole wall and as averaged around the hole, must be less than 10^{-10} m^2/s.*

The adequacy of this condition must be assessed in SR-Site.

It may also be noted that it follows from the design premises on buffer density – see section 3.2.2, that tolerances and acceptable damages e.g. from spalling, needs to be selected such that the initial saturated buffer densities lies within the limits stipulated by the density requirements. It also follows from the design premises on buffer and canister chemistry, see section 3.3.3, that the concentration of foreign materials in water infiltrating the open deposition holes should, at the time of disposal be limited.

Design implications for other barriers

The mechanical conditions of the deposition holes depend on the rock stress and the rock properties. This needs to be considered in the repository design with its selection of depth, suitable volumes and deposition tunnel orientation, see furtherTable 3-2.

3.4 Deposition tunnels and backfill

3.4.1 Restricting buffer expansion

Design premise

The backfill needs to restrict buffer expansion such that it maintains its designed properties, see section 3.2.2. It follows that:

- *Packing and density of the backfill, both at initial dry state and after complete water saturation must be sufficient to ensure a compressibility that results in a minimum buffer saturated density according to the conditions set out (i.e. 1,950 kg/m^3) with sufficient margin to loss of backfill and uncertainties.*

Design implications for other barriers

Fulfilment of the requirement implies

- restrictions on tunnel contour once packing density (percentage of pre-compacted blocks) are defined and
- restriction on inflows to allow backfill emplacement

Such criteria need to be developed as part of the design of a backfill concept and deposition tunnels.

3.4.2 Limiting advective transport

Design premises

According to SR-Can Main report /SKB 2006a, section 7.4/ the following function indicator criteria (BF1) should be upheld in the backfill to limitadvective transport:

- *Hydraulic conductivity < 10^{-10} m/s*
- *Swelling pressure > 0.1 MPa*

Scoping analyses /Joyce et al. 2008/ suggest that the hydraulic conductivity of the backfill may be higher, possibly up to 10^{-8} m/s, and need anyway not result in any lower overall "conductance" than resulting from the EDZ. Limited sections with even higher hydraulic conductivity could certainly be allowed. Nevertheless, the above criterion is kept as a design premise, but the analyses suggest that performance would not be too sensitive to later disturbances resulting in increased backfill conductivity.

It can be noted that these criteria are automatically upheld for a swelling backfill upholding the criteria concerning limiting buffer expansion set out in section 3.4.1. Furthermore, the criteria results in a requirement that the backfill material has to be able to self heal piping channels and other inhomogeneities that form during backfilling. This needs to be considered in selecting the composition of backfill material, see section 3.4.6.

3.4.3 Deposition tunnel – tolerances and excavation damages

From a long term safety point of view the possibility of an excavation damage zone is of potential significance. The analyses in SR-Can Main report /section 10.5.7 SKB 2006a/ suggest that even an EDZ is only important if it results in a continuous increase in transmissivity along the deposition tunnel. Furthermore, even with such a continuous EDZ, simulations with up to one and a half order of magnitude higher conductivity than the surrounding rock would not imply any major problem with respect to safety. However, from a practical standpoint it may be hard to prove that the EDZ has such a low conductivity. Furthermore, results of sensitivity studies in the SR-Can assessment suggest that the EDZ could be much more conductive than assessed as realistic in SR-Can without significant impact on the overall risk. For this reason a further sensitivity study has been undertaken /Jocye el al. 2008/. It shows that even with a connected EDZ transmissivity up to 10^{-8} m^2/s the impact of the EDZ is negligible. The analyses suggest that an even higher transmissivity would be acceptable, but this was not formally tested. Furthermore, the analysis was made on the Laxemar model used in SR-Can, it could not be fully excluded that the importance of the EDZ depends on the specific site properties. Requirements on the tunnel contour follows from the requirements on backfill density, see section 3.4.1 and need not be repeated here.

Design premises

Underground excavation should not significantly impair barriers and barrier functions, this implies the following criteria on the excavation:

- *Excavation induced damage should be limited and not result in a connected effective transmissivity, along a significant part (i.e. at least 20–30 m) of the disposal tunnel and averaged across the tunnel floor, higher than 10^{-8} m^2/s. Due to the preliminary nature of this criterion, its adequacy needs to be verified in SR-Site.*

3.4.4 Impacts on barrier functions from grouting, reinforcement and foreign materials

SR-Can Main report /SKB 2006a, section 4.2.10/ assumed that “low” pH cement, or other low pH grouting material, will be used for grouting of deposition holes and of deposition tunnels and also for potential shotcreting of deposition tunnels. At the time of completing SR-Can, these “low” pH materials were expected to have porewaters with pH ≤ 11, but the development of low pH materials was ongoing meaning that their final compositions were not available. Furthermore, although not explicitly stated in the SR-Can Main report, it was assumed that the deposition tunnels were not continuously shotcreted, since this would jeopardise the long term function of the buffer, and that there were no continuous grouting boreholes outside the tunnel perimeter, since this could create a highly permeable pathway once the grouting material has degraded. No analyses were conducted to see whether these restrictions could be relaxed.

SR-Can did not assess implications of rock boalts. Consequently, it is not possible at this stage to state any design premises on these. Instead SR-Site would need to consider implications, if any, of the re-enforcements suggested in the layout and design analysed.

Design premises

The following restrictions apply for grouting and reinforcement in deposition tunnels:

- *Only low pH materials (pH < 11)*
- *No continuous shotcrete*
- *Continuous grouting boreholes outside tunnel perimeter should be avoided*

The criterion on what is meant by “*continuous shotcrete*” would need further quantification. However, such a quantification would, at least partly, depend on the site properties since the distance would depend on the distances between important water conducting fractures intersection in the deposition tunnel. Thus, further specification cannot be made meaningful before a specific site is selected. It is noted that also the last requirement may need some further specification. The SR-Can analyses were not sufficiently detailed to provide more strict feedback. Instead, SR-Site and subsequent analyses would need to better substantiate this requirement. Other foreign materials must be limited, but there is currently no estimate of the nature or amounts that could be detrimental. Instead, SR-Site will need to verify that the estimated amounts of such material estimated by the repository design work does not jeopardise safety.

3.4.5 Repository depth and location

Factors of importance when selecting repository depth is discussed in SR-Can Main report /SKB 2006a, section 13.6.8/. In short it shows that repository depth needs to be selected where it is possible to find large volumes of rock fulfilling the specific requirements on deposition holes and deposition tunnels with regard to salinity and upconing, lengths and transport resistances of hydraulic travel paths to and from the repository, fracture frequency and frequency of connected transmissive fractures, groundwater pressure, rock stresses, initial temperature, potential for freezing during permafrost, surface erosion and inadvertent human intrusion. However, most of these aspects are covered by the criteria for selecting deposition holes (see sections 3.3.1 to 3.3.4) and deposition tunnels (see previous sub-section), discussed previously.

According to plans the repository should be constructed at a depth interval between 400–700 m. At this depth range there are also several site specific factors related to long-term safety that must be considered when selecting the repository depth. An overview of these factors is provided in Table 3-2 and SR-Can Main report /SKB 2006a, section 13.6.8/ describe the role each factor can play in the depth selection. The depth of the repository must, in general, balance the safety requirements for the repository and the constructability of the underground excavations required for the deposition tunnels and deposition holes. The safety requirements are largely influenced by the hydrogeology of the site, i.e. frequency and occurrence of transmissive fractures with depth while the constructability is mainly related to rock mechanics issues, i.e. stability of the deposition holes prior to emplacement.

Design premises

The following design premises apply:

- *The repository volumes and depth need to be selected where it is possible to find large volumes of rock fulfilling the specific requirements on deposition holes, see section 3.3.*
- *With respect to potential freezing of buffer and backfill, the requirement of temperatures favouring the mechanical properties of the canister (see section 2.3), surface erosion and inadvertent human intrusion the depth should be considerable. Analyses in the SR-Can assessments corroborate that this is achieved by prescribing the minimum depth to be as specified for a KBS-3 repository i.e. at least 400 m.*

Table 3-2. Engineering and safety factors considered for the recommendation of repository depth. "Up" implies that a shallow depth is preferable for this aspect, "down" implies that a deep depth is preferable for this aspect.

Engineering factors	Safety factors
Initial temperature: Up – lower in-situ temperature favorable for canister spacing.	**Initial temperature:** Considered in design, no direct effect.
Water inflow, grouting efforts: Up – lower groundwater pressure favorable. Down – if hydraulic conductivity decreases with depth.	**Salinity and upconing:** Up – possibly lower inflow to facility. **Groundwater pressure:** Up – marginal importance.
Rock stability, rock stress: Above a tentative triggering depth were stress conditions may be unfavorable for tunneling.	**Rock stress:** Above a tentative triggering depth were stress conditions may be unfavorable for long term effects around the deposition holes.
Available space, layout adaptation – 3D structural model: Undecided, site specific.	**3D structural model – layout adaptation, degree of utilization:** Site specific – fracturing, thermal properties, hydraulic properties, stability.
Degree of utilization – fracturing, thermal properties, inflow, stability: Site specific.	**Length and transport resistance of travel paths:** Down, longer paths generally favorable.
Environment (short term): Up, less excavated rock volume, possibly less inflow (drawdown), but if hydraulic conductivity decreases with depth inflow may also decrease with a deeper repository.	**Fracture frequency and Transmissivity:** Undecided, site specific.
Time and cost: Up, shorter access shafts and ramp.	**Inadvertent human intrusion:** Down, lower risk of intrusion, difficult to quantify.
Design of underground openings: Not affected.	**Freezing:** Down – reduces risk associated to permafrost. **Surface erosion:** No importance.

From a practical standpoint, there is need to strike a balance between the degree of utilisation resulting from applying the safety related criteria and other factors affecting the constructablity and efficiency of the repository. For this reason, depth is currently assessed and preliminary justified in the Site Engineering Report produced for each site /SKB 2009a, b/. The appropriateness of the selected depths needs to be verified in SR-Site.

3.4.6 Composition of backfill material

Design premises

There are no special requirements on the backfill material – as long as it fulfils the other design premises on the backfill. However, it should be noted that the backfill material has to be able to self heal piping channels and other inhomogeneities that form during backfilling.

To date, no requirements on limitations on the contents of accessory minerals in the backfill have been formulated. Such limits will be formulated at a later stage of the programme. They can be expected to be similar to, but quantitatively higher than the corresponding requirements on the buffer, see section 3.2.4 since their potential to damage the canister is less due to the longer distance to the canisters.

Design implications for other barriers

There are no direct design implications for other barriers.

3.5 Main tunnels, transport tunnels, access tunnels, shafts, central area and closure

3.5.1 Impact on barrier functions due to hydraulic properties

After closure, the main tunnels, transport tunnels, access tunnels, shafts and central area should not significantly impair barriers and barrier functions. This puts restrictions on the maximum allowed integrated conductivity, including potential EDZ, in these volumes. This issue was not addressed in SR-Can, but preliminary analyses made in 2008 /Joyce et al. 2008/ suggest that hydraulic conductivities less than 10^{-8} m/s are acceptable, and these low values need not be maintained everywhere along the tunnels nor in the central area.

Design premises

The resulting effective hydraulic conductivity after closure of the backfill material and EDZ must not unduly impair containment or retention properties of the repository. In particular the risk of penetration of oxygenated water to repository depth through these components must be considered. The following restrictions apply:

- *Below the location of the top sealing, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones. There is no restriction on the hydraulic conductivity in the central area.*
- *The top sealing has no demands on hydraulic conductivity.*
- *The depth of the top sealing can be adapted to the expected depth of permafrost during the assessment period, but must not be deeper than 100 m above repository depth*

The adequacy of these restrictions needs to be verified in SR-Site. It should also be noted that there are no specific requirements on the material used to close the central area, but there may be reasons to consider limits for the composition of this material.

Design implications for other barriers

It should be noted that the design premises concerns the combined effect of the closure material, the installation technique and the underground openings and their construction, including the EDZ.

3.5.2 Impacts on barrier functions from grouting and reinforcement

Grouting, reinforcement or foreign materials, must not significantly impair barriers and barrier functions. Ordinary cement, with its high pH is a potential problem, since high pH is detrimental to the buffer, see section 3.2.1. However, if ordinary cement is used far away from the deposition areas the possibility of a migration pH-plume disturbing the buffer should be small. This was, however, not analysed in SR-Can.

Design premise

There is a preliminary requirement on cement used e.g. for grouting and reinforcement:

- *only low pH (< 11) materials are allowed below the level of the top seal,*
- *other foreign materials must be limited – but the amounts considered in SR-Can are of no consequence.*

In the future it should be assessed whether the level above which ordinary cement can be accepted can be even deeper as this would simplify underground construction. Conclusions are likely to be site specific.

Design implications for other barriers

There are no implications on other barriers, but again it should be noted that the function of the closure will be a combination of the underground construction procedure and the material and the means and backfill material used to achieve closure.

3.5.3 Impact on barrier functions by boreholes

Boreholes were assumed to have the same properties as the surrounding rock in SR-Can. However, such a condition would not be necessary – and is impossible to prove in practice. Nevertheless, the sealing of the boreholes need to be sufficiently tight such that they do not form significant additional migration pathways too or from the deposition areas. Given the experiences with the tunnel backfill, see section 3.4.2, it seems unnecessary to demand more of the borehole seals than is demanded for the tunnels, i.e. an hydraulic conductivity of the borehole seal $< 10^{-8}$ m/s, which is ensured if the swelling pressure > 0.1 MPa.

Design premise

The following preliminary conditions apply:

- *Boreholes must be sealed such that they do not unduly impair containment or retention properties of the repository. This is preliminary achieved if the hydraulic conductivity of the borehole seal $< 10^{-8}$ m/s, which is ensured if the swelling pressure of the seal is > 0.1 MPa. This value need not be upheld in sections where e.g. hole passes highly transmissive zones.*

This condition needs further development, and the performance of the suggested means of sealing boreholes needs to be assessed in SR-Site in order to establish more final design premises.

3.5.4 Closure material and plugs

When the plug in the deposition tunnels has lost its function after the concrete has degraded the closure material of the main tunnels shall keep the backfill in the deposition tunnels in place and maintain its density and thereby its function. The same goes for the closure material in transport tunnels, ramp and shaft. It needs to keep the underlying material in place.

4 Summary of design premises

4.1 Comprehensiveness of design premises as regards long-term safety

The methodology for the safety assessment SR-Can, and that for the coming assessment SR-Site, is centred around the evaluation of a number of safety functions and how these are upheld over the one million year assessment period. For each safety function, there is a safety function indicator and in many cases also a safety function indicator criterion such that if the criterion is fulfilled, then the safety function is regarded as upheld, see Figure 4-1 and further Chapter 7 of the SR-Can Main report. It is important to note that the safety function indicator criteria are not the same as the design premises discussed in the present report. Whereas the former should be upheld throughout the assessment period, the latter refer to the initial state and must be defined such that they give a margin for deterioration over the assessment period. The copper coverage serves as an obvious example: The design premises is here that the copper coverage should be 5 cm whereas the safety function indicator criterion states that the coverage should everywhere on the canister surface be larger than zero, which is equivalent to stating that the canister's containing function is upheld.

Each safety function is influenced by a number of factors during the course of repository evolution, among them factors related to the initial state. For arguing comprehensiveness of the set of design premises established in this document it is of interest to check if all safety functions have been considered in the establishing of the design premises. This is done in Table 4-1. As seen in the table, each safety function has indeed been addressed by at least one design criterion. This indicates one type of comprehensiveness in the procedure used when establishing the design premises.

4.2 Overview of design premises

Table 4-2 provides an overview of the design premises and their foundation on SR-Can or other analyses. It should though be noted that the design premises are fully expressed by the text in Chapter 3 – this is only an overview table.

Table 4-1. Relation between safety functions and design premises.

Safety function (see Figure 4-1)	Corresponding design premise, section	Safety function (see Figure 4-1)	Corresponding design premise, section	Safety function (see Figure 4-1)	Corresponding design premise, section
C1	3.1.3	Bu7	3.4.5	R2a	3.4.3, 3.5.1, 3.5.3
C2	3.1.1	Bf1a	3.4.2	R2b	3.4.3, 3.5.1, 3.5.3
C3	3.1.2	Bf1b	3.4.2	R2c	3.4.5
Bu1a	3.2.2, 3.4.1	Bf1c	3.4.5	R2d	3.4.5
Bu1b	3.2.2, 3.4.1	R1a	3.3.3	R2e	3.4.5
Bu2	3.2.2, 3.4.1	R1b	3.3.3	R3a	3.3.1
Bu3	3.2.2, 3.4.1	R1c	3.3.3	R3b	3.4.5
Bu4	3.2.2 3.4.1	R1d	3.3.3	R4	3.4.5
Bu5	3.3.4	R1e	3.3.3, 3.4.4, 3.5.2		
Bu6	3.2.2, 3.4.1	R1f	3.3.3		

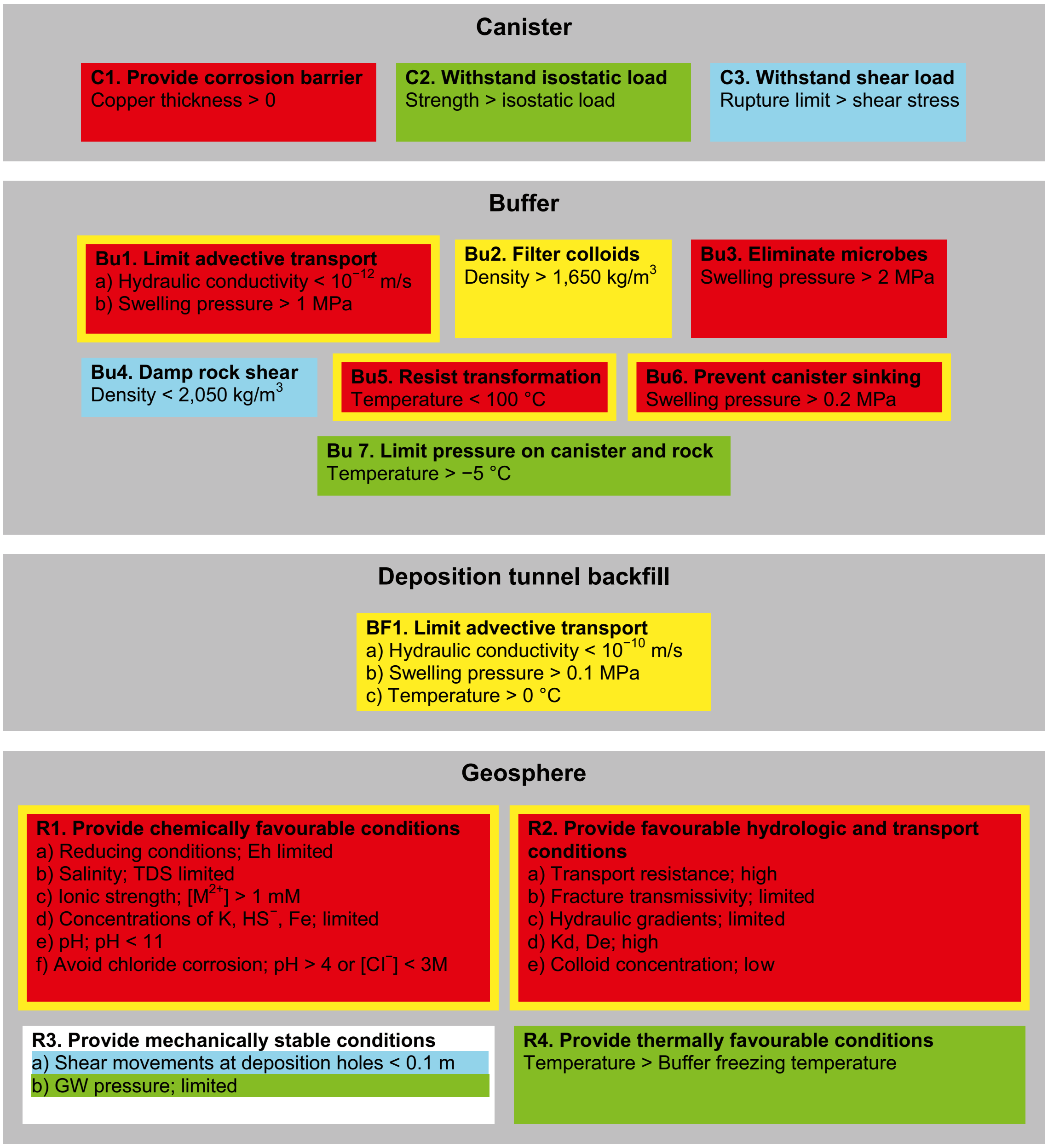

Figure 4-1. *Safety functions (bold), safety function indicators and safety function indicator criteria as stated in SR-Can Main report /SKB 2006a/. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).*

Table 4-2. Overview of design premises. However, it should be noted that it is the full text in Chapter 3 that applies, not this overview table.

Discussed in section	Heading	Design premises	Reference to SR-Can or subsequent analyses
3.1	**Canister**		
3.1.1	Withstand isostatic load	The canister shall withstand an isostatic load of 45 MPa, being the sum of maximum swelling pressure and maximum groundwater pressure.	SR-Can /SKB 2006a section 13.4.2/ and regarding the cast iron insert SR-Can /SKB 2006a section 13.5.1/. *Design basis case*: An isostatic load of 45 MPa being the summary of maximum swelling pressure and maximum groundwater pressure.
3.1.2	Withstand shear load	The copper corrosion barrier should remain intact after a 5 cm shear movement at 1 m/s for buffer material properties of a 2,050 kg/m^3 Ca-bentonite, and for all locations and angles of the shearing fracture in the deposition hole, and for temperatures down to 0°C. The insert should maintain its pressure-bearing properties to isostatic loads.	The *design basis case* is a 5 cm shear at 1 m/s with buffer as in SR-Can, i.e. with density < 2,050 kg/m^3 on a complete canister (i.e. both copper shell and cast iron insert) as described in section 2.3. More background is found in SR-Can /SKB 2006a sections 13.4.2 and 13.5.1/.
3.1.3	Provide corrosion barrier	A nominal copper thickness of 5 cm, also considering the welds.	SR-Can /SKB 2006a section 13.4.2/ – and additional discussion in section 2.4 above. SR-Can shows that 5 cm of copper is sufficient • to avoid canister failures due to corrosion if buffer is present, • to comply with risk criterion at both sites if buffer erosion is as pessimistically handled in SR-Can. Subsequent analysis shows that doubling the thickness would reduce risk by about a factor of 2. Since the impact of corrosion is site and design specific it will be necessary in SR-Site to verify that 5 cm is sufficient and re-address the safety related aspects of the BAT issue. In SKB's overall BAT argumentation, it is important to also consider negative implications of an increased thickness. *Design basis case:* Copper corrosion resulting from loss of buffer.
3.1.4	Prevent criticality	The spent fuel properties and geometrical arrangement in the canister should be such that criticality is avoided even if water should enter a defective canister.	See SR-Can /SKB 2006a section 7.4/. For the fuel types analysed in SR-Can it was concluded that (SR-Can /SKB 2006a section 10.3/) the risk for criticality is negligible at a KBS-3 type repository in the Swedish bedrock.

Discussed in section	Heading	Design premises	Reference to SR-Can or subsequent analyses
3.1.5	Additional canister design premises	To avoid gamma irradiation induced hardening and embrittlement of the cast iron material, the copper content in iron should be < 0.05%. The properties of the copper material are upheld providing the content of other elements are limitied according to: phosphorus 30–100 ppm, sulphur < 12 ppm, hydrogen < 0.6 ppm and oxygen less than some tens of ppm. The grain size should be < 800 µm (average grain size). The amount of nitric acid formed within the insert is limited by changing the atmosphere in the insert from air to > 90% argon. The maximum amount of water left in the insert is set to 600 g. The hydrogen content in copper material < 0,6 ppm. The copper shell and the insert must not be exposed to temperatures substantially above 100°C. For higher temperatures (i.e. above 125°C) the materials need to be further assessed. The copper material should be highly pure copper to avoid corrosion coupled to grain boundaries. Oxygen contents of up to som tens of ppm can, be allowed. Corrosion due to formation of nitric acid is analysed and neglected for radiation in the order of 1 Gray/h. Additional conditions are listed in Table 3-1.	SR-Can /SKB 2006c/.
3.2	**Buffer**		
3.2.2	Long-term durability of buffer material	After swelling the buffer should uphold the minimum swelling pressure 2 MPa and the hydraulic conductivity should not exceed 10^{-12} m/s independently of dominating cation and for chloride concentrations up to 1 M. After swelling the shear strength of the buffer must not exceed the strength used in the verifying analysis of the canisters resistance against shear loads. These conditions apply for temperatures down to –0°C and temperatures up to 100°C.	SR-Can /SKB 2006a sections 7.3.4 and 13.4.2/.
3.2.2	Prevent too large rock shear impacts and eliminate microbes	The initially deposited buffer mass should be such that it corresponds to a saturated buffer density in the volume initially filled with buffer that is: • less than 2,050 kg/m^3 to prevent too high shear impact on canister (see 3.1.2), and • higher than 1,950 kg/m^3, i.e. sufficiently high to ensure a swelling pressure of 2MPa with margin for possible loss of material.	Requirement a follows from the conditions set in section 3.1.2. Requirement b was assessed in SR-Can /SKB 2006b section 2.5.13/. A swelling pressure > 2 MPa is required to rule out microbial activity in the buffer. In SR-Can /SKB 2006a section 9.4.10/ it was shown that initial buffer density leading to saturated densities > 1,950 kg/m^3 is adequate for a sufficient swelling pressure, with margin to a moderate loss due to piping erosion.
3.2.3	Buffer thickness	The buffer dimensions used as reference dimensions in SR-Can shall be used, in addition to other requirements affecting the buffer and deposition hole geometry, in particular as stated by sections 3.2.2 and 3.3.5.	According to SR-Can /SKB 2006a section 13.3.4/, there are potential advantages with increased thickness with respect to loss of buffer, but no unambiguous conclusion.

Discussed in section	Heading	Design premises	Reference to SR-Can or subsequent analyses
3.2.4	Mineralogical composition of buffer material	The montmorillonite content of the dry buffer material shall be 75–90% by weight. The content of organic carbon should be less than 1 wt-%. The sulphide content should not exceed 0.5 weight percent of the total mass, corresponding to approximately 1% of pyrite. The total sulphur content (including the sulphide) should not exceed 1 wt-%.	SR-Can /SKB 2006b section 2.5.6/.
3.3	**Deposition holes**		
3.3.1	Adapted to the mechanicall conditions at the site	The following design premises apply: • Deposition holes are not allowed to be placed closer than 100 m to deformation zones with trace length longer than 3 km. • Deposition holes should, as far as reasonably possible, be selected such that they do not have potential for shear larger than the canister can withstand. To achieve this, the EFPC criterion should be applied in selecting deposition hole positions.	SR-Can /SKB 2006a section 9.4.5/. It should also be noted that it may be possible to reduce the respect distance of 100 m to some deformation zones based on an a site specific detailed and individual assessment of their properties combined with revised criteria for what fractures should be avoided in deposition holes.
3.3.2	Adapted to the hydrological and transport conditions at the site	The total volume of water flowing into a deposition hole, for the time between when the buffer is exposed to inflowing water and saturation, should be limited to ensure that no more than 100 kg of the initially deposited buffer material is lost due to piping/erosion. This implies, according to the present knowledge, that this total volume of water flowing into an accepted deposition hole must be less than 150 m^3. Fractures intersecting the deposition holes should have sufficiently low connected transmissivity (specific value cannot be given at this point).	SR-Can suggested inflows < 0.1 L/min was sufficient for acceptable loss of buffer. This has been re-evaluated and the current rule is based on a more detailed assessment by /Åkesson et al. 2010/. Connected transmissivity was not assessed in SR-Can, but it was shown to be an advantage to avoid holes with high connected T. Will need to be further assessed in SR-Site. SR-Can also suggested that special respect distances to highly transmissive deformation zones were not needed. Should be reassessed in SR-Site, since answer may be site and layout specific.
3.3.3	Adapted to the chemical conditions at the site	The groundwater composition in rock volumes selected for deposition holes should, prior to excavation, fulfil the SR-Can function indicator criteria R1. Provide chemically favourable conditions: • Reducing conditions • Salinity; TDS limited • Ionic strength; M^{2+}] > 1 mM • Concentrations of K, HS^-, Fe; limited • pH; pH < 11 • Avoid chloride corrosion; pH > 4 or [Cl−] < 3M When quantitative criteria are not given, the term "limited" is used to indicate favourable values of the safety function indicators. The requirements concern conditions prior to excavation, whereas SR-Site would need to verify that the long term evolution of these conditions still result in a safe repository.	See SR-Can /SKB 2006a section 7.5, Figure 7.2/.

Discussed in section	Heading	Design premises	Reference to SR-Can or subsequent analyses
3.3.4	Adapted to the thermal conditions at the site	Buffer geometry (e.g. void spaces), buffer water content and distances between deposition holes should be selected such that the temperature in the buffer is < 100°C.	Follows from the thermal requirements on the buffer (see section 3.2.1) and discussed in SR-Can /SKB 2006a 13.6.7/. Principles of dimensioning are found in /Hökmark et al. 2009/. It is based on reference design values for total decay power of encapsulated fuel elements, thermal properties and geometry of the buffer, thermal properties and geometry of the backfill and geometry of deposition holes and tunnels.
3.3.5	Not significantly impair barriers and barrier functions	Before canister emplacement, he connected effective transmissivity integrated along the full length of the deposition hole wall and as averaged around the hole, must be less than 10^{-10} m^2/s.	Not assessed in SR-Can. Conditions for EDZ (due to spalling) was primarily assessed by /Joyce et al. 2008/ but need verification in SR-Site.
3.4	**Deposition tunnels and backfill**		
3.4.1	Restrict buffer expansion	Packing and density of the backfill, both at initial dry state and after complete water saturation, must be sufficient to ensure a compressibility that results in a minimum buffer saturated density according to the conditions set out (i.e. 1,950 kg/m^3) with sufficient margin to loss of backfill and uncertainties.	Follows from the design premises on the buffer, section 3.2.2. SR-Can concluded that the deposited density of Friedland clay assumed in SR-Can was sufficient to fulfil long-term requirements on tunnel backfill including hydraulic conductivity and compressibility. However, this conclusion assumed idealised tunnel contour and packing. Recent studies suggest a need to use more competent backfill materials. There is also a need to comment on the conditions for the backfill and glacial water. These conditions are not suggested to be part of the backfill design, but needs to be addressed in SR-Site!
3.4.2	Limit advective transport	The following function indicator criteria (should be upheld in the backfill to limit migration: • Hydraulic conductivity < 10^{-10} m/s. • Swelling pressure > 0.1 MPa.	See SR-Can /SKB 2006a section 7.4/.
3.4.3	Not significantly impair barriers and barrier functions – EDZ	Excavation induced damage should be limited and not result in a connected effective transmissivity, along a significant part (i.e. at least 20–30 m) the disposal tunnel and averaged across the tunnel floor, higher than 10^{-8} m^2/s. The tunnel contour needs to be smooth enough to allow packing backfill density selected in order to fulfil the criteria given in section 3.4.1.	Tunnel contour requirement follows from requirement 4.1. EDZ is discussed in SR-Can /SKB 2006a section 13.6.6/. SR-Can showed that and EDZ with a K 1.5 order of magnitude higher than surrounding rock has no negative impact. The T_{EDZ} can thus be much higher. The value in the criterion, 10^{-8} m^2/s was shown in a preliminary study to SR-Site /Joyce et al. 2008/, to be of no consequence. Due to the preliminary nature of this criterion, its adequacy needs to be verified in SR-Site.

Discussed in section	Heading	Design premises	Reference to SR-Can or subsequent analyses
3.4.4	Not significantly impair barrier functions – grouting, reinforcement or foreign materials.	Grouting and reinforcement in deposition tunnels: • Only low pH materials (pH < 11). • No continuous shotcrete. • Continuous grouting boreholes outside tunnel perimeter should be avoided.	SR-Can /SKB 2006a section 13.6.4/. This was assumed in SR-Can and no analyses were conducted to see whether these restrictions could be relaxed. The criterion on what is meant by “continuous shotcrete” would need further quantification. However, such a quantification would, at least partly, depend on the site properties since the distance would depend on the distances between important water conducting fractures intersection in the deposition tunnel. Thus, further specification cannot be made meaningful before a specific site is selected.
3.4.5	Favourable hydrologic, transport, thermally mechanical and chemical conditions. Adapted to human activities. Repository depth and location.	The repository volumes and depth need to be selected where it is possible to find large volumes of rock fulfilling the specific requirements on deposition holes, see section 3.3. With respect to potential freezing of buffer and backfill, the requirement of temperatures favouring the mechanical properties of the canister, surface erosion and inadvertent human intrusion the depth should be considerable. Analyses in the SR-Can assessments corroborate that this is achieved by prescribing the minimum depth to be as specified for a KBS-3 repository i.e. at least 400 m.	Discussed in SR-Can /SKB 2006a section 13.6.8/.
3.5	**Main tunnels, transport tunnels, access tunnels, shafts and central area and closure**		
3.5.1	Not significantly impair barrier functions – excavation, closure and top sealing.	• Below the location of the top sealing, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones. There is no restriction on the hydraulic conductivity in the central area. • The top sealing has no demands on hydraulic conductivity. • The depth of the top sealing can be adapted to the expected depth of permafrost during the assessment period, but must not be deeper than 100 m above repository depth.	This issue was not addressed in SR-Can, but preliminary analyses made in spring 2008 /Joyce et al. 2008/ suggests hydraulic conductivities less than 10^{-8} m/s is acceptable, and these low values need not be maintain everywhere along the tunnels and not in the central area. The adequacy of these design premises needs to be verified in SR-Site. It should also be noted that there are no specific requirements on the material used to close the central area, but there may be reasons to consider limits for the composition of this material.
3.5.2	Not significantly impair barrier functions – grouting, reinforcement and foreign materials.	Only low pH (< 11) materials are allowed below the level of the top seal. Other foreign materials must be limited – but the amounts considered in SR-Can is of no consequence.	These conditions were assumed in SR-Can. In the future it should be assessed whether the level above which ordinary cement can be accepted can be even deeper as this would simplify underground construction. This is a strong need from engineering design.

Discussed in section	Heading	Design premises	Reference to SR-Can or subsequent analyses
3.5.3	Limit water flow – sealing of boreholes.	Boreholes must be sealed such that they do not unduly impair containment or retention properties of the repository. This is preliminary achieved if the hydraulic conductivity of the borehole seal < 10^{-8} m/s, which is ensured if the swelling pressure of the seal is > 0.1 MPa. This value need not be upheld in sections where e.g. the hole passes highly transmissive zones. This condition needs further development, and the performance of the suggested means of sealing boreholes needs to be assessed in SR-Site in order to establish more final criteria.	Need to assess importance in SR-Site.

5 References

Andersson H, Seitleam F, Sandström R, 1999. Influence of phosphorous and sulphur as well as grain size on creep in pure copper. SKB TR-99-39, Svensk Kärnbränslehantering AB.

Andersson H, Seitleam F, Sandström R, 2007. Creep testing and creep loading experiments on friction stir welds in copper at 75°C. SKB TR-07-08, Svensk Kärnbränslehantering AB.

Brissonneau L, Barbu A, Bocuet J L, 2004. Radiation effects on the long-term ageing of spent fuel storage containers, RAMTRANS Vol. 15, No. 2, pp. 121–130.

Börgesson L, Hernelind J, 2006. Consequeces of loss or missing bentonite in a deposition hole. A theoretical study. SKB TR-06-13, Svensk Kärnbränslehantering AB.

Cosgrove J, Stanfors R, Röshoff K, 2006. Geological characteristics of deformation zones and a strategy for their detection in a repository. SKB R-06-39, Svensk Kärnbränslehantering AB.

Dies K, 1967. Kupfer und Kupferlegierungen in der Technik. Springer-Verlag, Berlin/Heidelberg, New York.

Fälth B, Hökmark H, 2006. Seismically induced slip on rock fractures. Results from dynamic discrete fracture modelling. SKB R-06-48, Svensk Kärnbränslehantering AB.

Gubner R, Andersson U, Linder M, Nazarov A, Taxén C, 2006. Grain boundary corrosion of copper canister weld material. SKB TR-06-01, Svensk Kärnbränslehantering AB.

Gubner R, Andersson U, 2007. Corrosion resistance of copper canister weld material. SKB TR-07-07, Svensk Kärnbränslehantering AB.

Hökmark H, Lönnqvist M, Kristensson O, Sundberg J, Hellström G, 2009. Strategy for thermal dimensioning of the final repository for spent nuclear fuel. SKB R-09-04, Svensk Kärnbränslehantering AB.

Joyce S, Hoek J, Hartley L, 2008. SR-Site Pre-modelling: Sensitivity studies of hydrogeological model variants for the Laxemar site using CONNECTFLOW. SKB R-08-108, Svensk Kärnbränslehantering AB.

King F, Ahonen L, Taxén C, Vuorinen U, Werme L, 2001. Copper corrosion under expected conditions in adeep geologic repository. SKB TR-01-23, Svensk Kärnbränsehantering AB.

King F, 2004. The effect of discontinuities on the corrosion behaviour of copper canisters. SKB TR-04-05, Svensk Kärnbränsehantering AB.

Munier R, Hökmark H, 2004. Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB.

Munier R, 2006. Using observations in deposition tunnels to avoid intersections with critical fractures in deposition holes. SKB R-06-54, Svensk Kärnbränslehantering AB.

Munier R, 2007. Demonstrating the efficiency of the EFPC criterion by means of sensitivity analyses. SKB R-06-115, Svensk Kärnbränslehantering AB.

SKB, 2006a. Long term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project. SKB TR-06-09, Svensk Kärnbränslehantering AB.

SKB, 2006b. Buffer and backfill process report for the safety assessment SR-Can. SKB TR-06-18, Svensk Kärnbränslehantering AB.

SKB, 2006c. Fuel and canister process report. SKB TR-06-22, Svensk Kärnbränslehantering AB.

SKB, 2006d. Climate and climate-related issues for the safety assessment SR-Can. SKB TR-06-23, Svensk Kärnbränslehantering AB.

SKB, 2006e. Initial state report for the safety assessment SR-Can. SKB TR-06-21, Svensk Kärnbränslehanteing AB.

SKB, 2006f. Kapsel för använt kärnbränsle, Konstruktionsförutsättningar. SKB R-06-02, Svensk Kärnbränsehantering AB.

SKB, 2009a. Forsmark Site Engineering Report. Guidelines for Underground Design, Step D2. SKB R-08-83, Svensk Kärnbränslehantering AB.

SKB, 2009b. Laxemar Site Engineering Report. Guidelines for Underground Design, Step D2. SKB R-08-88, Svensk Kärnbränslehantering AB.

Svensson U, 2006. The Laxemar and Forsmark repositories. An analysis of the water inflow distribution. SKB R-06-102, Svensk Kärnbränslehantering AB.

Åkesson M, Kristensson O, Börgesson L, 2010. THM modelling of buffer, backfill and other system components. SKB TR-10-11, Svensk Kärnbränslehantering AB.

ISSN 1404-0344
CM Gruppen AB, Bromma, 2009