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SKB's response to NEA's second questionnaire on post-closure safety in SKB's licence application

This document presents SKB's responses to the NEA international review team's second questionnaire on post-closure safety.

The responses are provided as part of the International Peer Review undertaken by OECD/NEA as requested by the Swedish Government of SKB's reporting on post-closure safety in the licence application for a spent nuclear fuel repository.

The responses provided are to the questions specified in the OECD/NEA document **NEA/RWM/PEER(2011)3** dated 26 July 2011. NEA's brief introduction and the original questions are included in the text below. SKB's responses are given in bold after each question.

In the responses, references on the formats TR-xx-xx and R-xx-xx refer to SKB reports of the TR and R series, respectively. Many of these are included in the licence application and all are available at www.skb.se.

In addition to this document, the internal report requested in Q 2.8.14 and the Table requested in Q 2.8.9 (including also data requested in Q 2.8.10) will be delivered as separate documents by September 15, 2011. The English translation of R-10-08, requested in Q 2.8.15 is expected to be delivered at the end of October 2011.

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1. INTRODUCTION

At the request of the Swedish government, the OECD-NEA International Review Team (IRT) is examining the application by SKB for a construction license of a spent fuel repository in Sweden. The IRT members encompass a diverse knowledge- and experience-set and, so far, have reviewed the information in SKB TR-11-01 from individual and unique view points.

In order to reflect this diversity, the 227 questions posed by the IRT members in this second questionnaire[1] are not pooled by subject but are presented as received from each individual IRT member. As a result, SKB may find partial overlap in some of the questions, in which case the provision of one answer would suffice, providing that SKB indicates which questions are being answered in one response.

The questions in this second questionnaire are numbered and are organized per IRT member in sections 2.1 through 2.9.

SKB should anticipate receiving a third questionnaire, based on a further review of TR-11-01, more detailed and supplementary documents such as the process reports, and an analysis of the responses received.

1 2 Questions from IRT Members

2.1 Questions from IRT Member 1

2.2.1 Initial State

The following set of questions is related to the technical feasibility of the construction (including manufacturing) of the buffer, backfill and closure.

Q 2.1.1 What is the timing of the emplacement sequence of the buffer, canister and backfill for a specific deposition tunnel?

The emplacement sequence for each of the components is described in detail in the respective production reports. A summary can be found in chapter 2 in SKB R-08-59.

Q 2.1.2 Related to the open slot between the canister and the bentonite blocks, has the buffer time evolution been assessed under operational repository-like conditions (e.g., with respect to temperature and humidity)?

Does this question refer to the slot or “operational repository-like conditions”?
The open slot between the canister and bentonite (as well as the pellet filled slot between the blocks and the rock are considered in the calculations of the peak temperature. The slots are also considered in the assessment of the swelling pressure of the buffer. Only the outer slot is

[1] Questionnaire 1, the NEA standard questionnaire with questions related to principles and good practice for safety cases, was submitted to SKB April 26, 2011 and answers were received June 14, 2011.

considered in the assessment of the buffer hydration, since the inner slot will have limited impact on the process.

A single deposition tunnel will be backfilled and sealed in a rather short time period (~1-2 months). The conditions during the transient backfilling phase are therefore not considered in the assessment.

Q 2.1.3 Has the pellet emplacement in a deposition hole been assessed under wet conditions?

Pellet emplacement under wet conditions is assumed to be problematic. A buffer protection sheet is therefore installed in wet depositions holes. Pellets emplacement will take place immediately after removal of the protection. This is further discussed in the Buffer Production Report. Deposition holes with large inflows will not be used (see also response to Q 2.4.4).

Q 2.1.4 Important bentonite properties such as swelling pressure and hydraulic conductivity are typically expressed as a function of the dry density. This is so in SR-Site for the backfill but not for the buffer. Is there any particular reason for that?

Expressing buffer properties as function of saturated density has a strong tradition in the Swedish program. There was an attempt for a change in the SR-Can assessment, but this proved unsuccessful.

Q 2.1.5 Two different types of bentonite are considered in SR-Site. Has a comparative study of their different hydraulic and mechanical (including swelling pressure and strain for different dry densities) properties been performed?

Yes, a comparison of swelling pressure can be found in Figure 5-14, more details are given in SKB TR-06-30.

2.1.2 Long Term Performance

The following set of questions is related to processes which might be relevant for the long term performance of the buffer, backfill and closure.

Piping erosion

Q 2.1.6 The model used in SR-Site for determining the buffer bentonite mass eroded by water is an empirical one. Does SKB consider this approach sufficient and why or, alternatively, is SKB planning to develop a hydro-mechanical model based on established physical laws in order to reduce existing uncertainties?

A model based on physical laws may have advantages, but may also be difficult to verify. Data for shear resistance of very loose clay, friction between particles, attractive and repulsive forces, etc need to be determined. It is unclear whether uncertainties really could be reduced. Piping is only relevant in the early evolution of the repository and therefore no long-term extrapolation of the modeling results is needed. Hence, it could be justified to use a model based directly on experimental observations. Many geotechnical models are in fact empirical.

Saturation

Q 2.1.7 The water retention properties of bentonites, as expressed through a water retention curve (experimentally derived), usually indicate that even under full saturation conditions the bentonite is still in a suction state and hence it can keep absorbing water. Has SKB observed this bentonite performance as well? If so, has SKB assessed this performance for different dry densities and temperatures, under confined conditions?

It is correct that that a fully water saturated bentonite sample still has suction if it is unconfined and not in contact with free water. The suction is equal to the swelling pressure at that density. However, the suction will decrease if a confinement is applied to the sample and be completely lost if the confining pressure is equal to the swelling pressure at that density. This performance is assessed and used in the THM models of the bentonite. Both swelling pressure and suction have been measured at different densities and temperatures.

Swelling

Q 2.1.8 Has the time evolution of the swelling strain under vertical stress been determined for different temperatures? Is there any significant difference in performance between the two proposed bentonites?

The time evolution of the swelling strain is controlled by the swelling pressure (or suction) and the hydraulic conductivity of the bentonite. This is in agreement with the consolidation theory of soils (although consolidation refers to compression instead of swelling). The influence of temperature corresponds thus to the influence of temperature on the hydraulic conductivity (which in turn actually is proportional to the water viscosity) and the influence of temperature on suction. The influence of temperature on the hydraulic conductivity is taken into account by the THM material models but not the influence on suction. The influence of temperature on suction has been investigated for the reference buffer material but not so thoroughly for the backfill. The mechanisms are the same for the buffer and backfill but the values of hydraulic conductivity and suction differ between the materials.

Colloid erosion

Q 2.1.9 SKB recognizes an incomplete conceptual understanding of buffer erosion (P.31, TR-11-01). Beyond the current approach and use of pessimistic hypothesis related to this process, is SKB also planning to fill this knowledge gap and reduce the associated uncertainty?

SKB do have an extensive R&D program on the issues of colloid formation and erosion. This is mentioned in section 15.7.3 of the SR-Site main report and presented further in the 2010 R&D program /SKB TR-10-63/.

2.2 Questions from IRT Member 2

2.2.1 Initial State

The following set of questions is related to the technical feasibility of the construction (including manufacturing) of the canister.

Q 2.2.1 How did SKB come to the conclusion to use copper as a barrier material for the canister? Where is this documented? (There seems to be no documentation about any type of selection process in SR-Site.)

The selection of canister material was considered early on in the KBS-project. In the KBS-1 report (1977) a lead-titanium canister was chosen for vitrified reprocessing waste. For disposal of spent nuclear fuel a material with longer service life was sought for. An inventory of possible encapsulation materials was made and on the basis of this inventory copper and two ceramic materials (alpha-aluminum oxide and a glassceramic material of the beta-spodume type) were chosen for closer study. In the selection of materials, availability, economy and ease of fabrication were also taken into consideration. The KBS-2 report published in 1978 recommended canisters of copper, but stated that studies of different ceramic materials would continue. There were still uncertainties related to the risk of delayed fracturing of ceramic canisters. In the KBS-3 report published in 1983 it was stated that the canisters would be made of copper.

This is documented in the KBS-1 and KBS-2 reports with references. For a brief account see the English summary of R-10-40.

Q 2.2.2 In which way does SKB plan to develop quality-control data for the production in real world dimensions? How will quality control at the production site be handled?

The manufacturing process, including the quality controls, will be qualified under supervision of an authorized body. A general overview of the planned quality controls is described in the Canister Production Report (TR-10-14 chapter 5) and TR-10-12 section 5.3.

Q 2.2.3 Related to the welding of the canister, so far only few demonstration welds have been made according to SR-Site. Will there be further investigation to give a detailed set of data? Presently SR-Site gives only very general explanations about the application of standard technology. During the demonstration experiments the need for improvement was shown. Would SKB agree?

The welding process has been demonstrated in the following steps:

1. **In 2004, 20 full weld cycles were produced on 20 lids in a production-like rate of (almost) 1 lid/day. No defects were found, but since the welding procedure was not optimized in regards of tool length a so-called joint line hooking discontinuity reduced the copper corrosion barrier by up to 4.5 mm. In addition, the welds were produced by manual control of the welding parameters by the welding operator to keep the tool temperature within its process window of +/- 60°C (below 790°C risk of defects, and above 910°C risk of tool fracture). During the 20 welds the tool temperature spanned the whole tool temperature process window, but did not go outside.**
2. **In 2005, an optimized welding procedure in regards of tool length was demonstrated during 20 shorter weld cycles containing the overlap sequence (where the maximum joint line hooking almost always occurs) resulting in a maximum joint line hooking of 1.5 mm.**
3. **In 2010-2011, within the scope of a doctoral thesis, an automatic welding procedure was developed and demonstrated during 8 full weld cycles. During these welds the tool temperature was maintained within +/- 10°C i.e. one-sixth of the process window. /Ref TR-10-14 section 5.5 and SKBDoc no. 1175162 and1175236/.**

Q 2.2.4 How will failures in the process of welding be treated? Is there a solution for incorrectly welded canister lids? Is there a process description to handle such cases? Will there be a procedure for repair? Will the canisters be rejected and have to be unloaded again? How will it be prevented that canisters with not-acceptable welds be deposited?

At the present stage, repair of welds is not considered as part of the reference method for welding, i.e. if the welding process fails the canister will be rejected and reloaded. In the upcoming years, trials are planned to examine if it is possible to develop a reliable and efficient technique for repair of some types of welding failures. The quality control of the welds is planned to be done in two steps; firstly the process control of the welding system will make sure that the welding parameters not have been outside the process window and secondly non-destructive testing will be applied on all copper welds by the use of qualified methods. /TR-10-14 section 5.5 and 6.3/.

2.2.2 Long Term Performance

The following set of questions is related to corrosion processes which might be relevant for the long term performance of the canister.

Q 2.2.5 Experiments with test canisters (minican) showed high corrosion rates, as determined by electrochemical measurements. Were these results included in the safety assessment or will they and how?

The electrochemically corrosion rates reported from the Minican project at Äspö are not used directly in the safety assessment. These on-line measurements will be compared with analyses of the actual corrosion of the canisters and electrodes when demounted, and after that the results will be part of the knowledge base of the corrosion processes. The electrochemical measurements are known to overestimate corrosion as they measure any reaction including electrons at the surface. Regarding the general approach for corrosion assessment in SR-Site see also the response to Q 2.2.7.

Q 2.2.6 Are data available concerning the corrosion behavior of the welds? Which measurements were made to evaluate the corrosion behavior?

Corrosion in the welds is discussed in the state-of-the-art report on corrosion (SKB TR-10-67, section 5.2.5) and references therein. Studies have been performed on possible differences in potential between weld and base material, but no preferential corrosion of the welds could be seen. The FSW tool is cathodic to the weld material, which means any particles lost from the tool would be cathodically protected and would not corrode to cause an aggressive environment.

Q 2.2.7 There are only very few long-time corrosion experiments with coupons and/or test canisters. During evaluation of the results some of the samples were damaged. Are there additional experiments or will there be such? Which experimental data were used for long-term assessment?

There are additional long-term experiments going on and further ones are planned.

Generally, following the safety assessment methodology, the corrosion assessment starts with the detailed knowledge of the corrosion processes, backed-up by laboratory as well as larger scale and more long-term experiments. From this the handling approach for each process is formulated (see the Fuel and canister process report, SKB TR-10-46) and any need for quantitative analyses identified. In SR-Site the corrosion calculations are either mass balances (pessimistic) or transport calculations for corrosion processes rate-limited by transport of corroding agents or corrosion products. Measured corrosion rates are not directly used in the assessment.

This answer is also a response to Q 2.2.5.

Q 2.2.8 Copper corrosion strongly depends on the formation of protective layers. SR-Site in general is giving the impression that cuprite is the main corrosion product. This does not seem to be completely supported by the results from the minican experiments. Would SKB agree? How does SKB treat the possible layers from corrosion products and how does this affect the lifetime assessment?

The lifetime assessment in SR-Site uses pessimistic approaches to estimate the corrosion rates, based on the transport of corroding agents by diffusion and advection. Also mass balances are used to bound the amount of corrosion. The assumption that cuprite is the corrosion product is one further means of being pessimistic (more copper atoms oxidized per oxygen molecule). The influence of corrosion product layers on corrosion rates is discussed in the state-of-the-art-report on corrosion (SKB TR-10-67, section 5.2), concluding that in a sealed repository the extent of general corrosion is limited by the general lack of oxidants.

Studies of localised corrosion on copper in repository environment suggest that there is no permanent separation of anodic and cathodic sites, why a form of under-deposite corrosion or surface roughness appears, rather than classical pitting (SKB TR-10-67, section 5.3). This is taken into account by adding a term of ±50 µm to the corrosion by the entrapped oxygen.

It is not fully clear what results from the Minican experiments that are referred to. The types of corrosion products will be analysed when the canisters are dismounted (a first canister was dismounted in August 2011, but no results are available yet).

This answer is a response also to Q2.2.11.

Q 2.2.9 Usually, there is no strict linear progress of corrosion if one considers layer formation. Thus one would expect higher rates for the initial state followed by slower processes. SR Site refers to higher corrosion rates in the initial state only, due to changes in the environment. If these changes take place they affect the stability and formation of the layers during the initial and the following states of the repository. By which procedure is this effect take into account?

The higher corrosion rates initially refers to the corrosion under oxidative conditions, with lower corrosion rates for the later stage with corrosion by sulphide, limited by the transport of sulphide to the canister. No account is taken for any slowing of the processes by the layer formation, or by the chemical change of the first formed copper oxide into copper sulphide. (The latter is discussed in SKB TR-10-67, section 5.2.3).

This answer is a response also to Q2.2.11 and 2.2.13.

Q 2.2.10 Transport processes strongly influence the kinetics of chemical reactions. From the assessment given in SR-Site it is not clear how transport of corrosion products is acknowledged in the safety assessment. There is information about transport of corrosive substances, but not of corrosion products, it seems.

The main corrosion products are solids (sulphide, oxides) and transport by diffusion or advection is therefore not considered. In the what-if-calculations of the suggested corrosion of copper by water, the transport of formed hydrogen gas is calculated as the rate limiting step, using the same transport models as for transport of sulphide to the canister (see SKB TR-10-66, section 5.4).

Q 2.2.11 How is the influence of changes in the environment of the canister, due to the corrosion products, on the corrosion processes considered?

See response to Q2.2.8 and 2.2.9.

Q 2.2.12 There is a discussion about copper corrosion in pure water without oxygen. If this process has to be taken into account, corrosion rates higher than assessed in SR-Site have to be considered. Are there experiments that deal with this type of corrosion? The theoretical assessment given in TR-10-30 is known but is it sufficient?

There have been different attempts to reproduce the experimental results on corrosion of copper in pure water by Hultquist and colleagues, but without success (for a review, see e.g. SKB TR-10-69; this report was published after the license application).

In SR-Site, experimental corrosion rates are not used directly. Rather, mass balances and transport limited processes are analysed. This approach is described in the Corrosion calculations report (SKB TR-10-66, chapter 3).

The corrosion at anoxic conditions with hydrogen gas production is evaluated as a what-if-calculation (mentioned in section 12.6.2 p. 599 of the SR-Site main report with details in section 5.4 in TR-10-66). A bounding case with the eroded buffer model gives a corrosion depth of a few mm in 10^6 years also for the deposition hole with the highest flow rate. Any hydrogen gas present in the groundwater is pessimistically disregarded. Also the early phase with an unsaturated pore space in the buffer, that could potentially be filled with hydrogen gas is analysed, but gives corrosion depth in the µm range. So – the theoretical assessment of the stability of the suggested corrosion product is not sufficient, but it is complemented in SR-Site with assessments of corrosion depth under the assumption that the process exists.

This answer is a response (partly) also to Q 2.2.13.

Q 2.2.13 If one assumes the possibility of copper corrosion in pure water in anoxic conditions, what would be the influence under repository conditions? Are there experimental data available for the assessment of copper corrosion under anoxic repository conditions? What is the behavior of copper that formed corrosion products under oxygen and later is exposed to anoxic conditions?

See response to Q2.2.9 and Q2.2.12.

Q 2.2.14 Regarding SCC, there are no values for critical tensile stresses that would lead to SCC. If one considers mechanical stress onto the canister, what would be the influence of the mechanical properties of the copper canister and how would it be ensured that all production canisters will fulfill this demand? What magnitude of tensile stress is expected and what magnitude of tensile stress is considered detrimental? The canister process report TR-10-46 does not seem specific on this point.

The stresses in the copper shell are thoroughly analysed in the Design analysis of the canister (SKB TR-10-28, section 6.2) and its supporting documents, for different loads as well as for residual stresses. Tensile stresses at the outside of the copper shell cannot be excluded. The assessment of failure against different criteria, including stress/strain criteria, is analysed in chapter 8 of the same report. High strains are only observed at geometric discontinuities and would not threaten the global integrity. Description of the production of canisters and the means to assure the stated quality is found in the report on Design, production and initial state of the canister (SKB TR-10-14).

For SCC, approaches based on the effect of stress is discussed in section 6.2.2.3 of the state-of-the-art report on copper corrosion (SKB TR-10-67), but shows the difficulties in using stress-related criteria to exclude SCC. In the dedicated report on SCC mechanisms (SKB TR-10-04, chapter 4) the use of a decision tree for determining the susceptibility of copper to SCC is

presented, and it is shown that other factors are limiting for the occurrence of SCC under repository conditions.

2.3 Questions from IRT Member 3

These questions relate to the geology of the Forsmark site, the initial state of the underground openings and geosphere processes (TR-11-01 Chapters S, 4, 5.2, 7.4.5).

Q 2.3.1 Where is it documented that no major design changes have occurred in recent years and that the identified set of processes of importance for long term safety is stable? (P.16)

(General answer to Q 2.3.1 to 2.3.5: These reference questions refer to the summary where, deliberately, no detailed references are given in order to not burden the text.)

The main features of the KBS-3 design (5 cm copper canisters with a strong insert, surrounded by a 35 cm benonite buffer at approximately 500 m depth in saturated, granitic rock) were presented in the KBS-3 report (in Swedish), mentioned on p 19. (The detailed reference is given in the main text. The historical development of the KBS-3 design is described elsewhere in the license application, in Swedish. For an overview, see the English summary of R-10-40.)

Regarding the stability of the set of processes, the identification of each process can be traced in the FEP database, as documented in the SR-Site FEP report, TR-10-45. A more straightforward way to see that there have been no major changes is, however, to compare the set of processes in the SR 97 process report, TR-99-07 published in 1999, to the SR-Site process, as tabulated in Tables 7-2 through 7-6 in the SR-Site main report.

Q 2.3.2 Where is the average distance between transmissive fractures at repository depth documented (primary data set)? (P. 17)

The matter is discussed in section 8.4.2 of SDM Site Forsmark (TR-08-05), where also underlying references to the actual measurements are provided. Specific data, with reference to the actual data, are listed in table 8-4 of that same report.

Q 2.3.3 Where are the *in situ* swelling pressures of the bentonite in deposition holes documented (1-15 MPa)? (P. 30)

The swelling pressure and the hydraulic conductivity of the bentonite is a function of density of the material (and to some extent the composition of the groundwater). The values for the installed buffer are given in Chapter 5.5.3 of the main report and in the Buffer production report.

Q 2.3.4 Where is the *in situ* hydraulic conductivity of the bentonite buffer in deposition holes documented (<1E-12 m/s)? (P. 30)

See response to Q 2.3.3.

Q 2.3.5 Where is the contribution to safety of the deposition tunnel backfill, and plug and clay in ramp and shaft documented? (P. 37)

The design premises related to long-term safety for the deposition tunnel backfill are given in section 5.6.1. The other components are discussed in section 5.7.1. Safety functions for the

deposition tunnel backfill are discussed in sections 8.3.3 and 8.4.4. There are no safety functions for the other components mentioned in the question.

Q 2.3.6 The “target area” as defined in Figure 4-5 seems to also include unsuitable regions (SE of ENE062A), what is the purpose of this term? (P. 105)

The purpose of this term is to highlight the part of the site investigation area (candidate area) that during the site investigation process was selected as suitable for hosting a repository and therefore became the “target area” for the continued site investigation. This selection was made based on data and modelling from the initial site investigations and the purpose was to focus the remaining data selection to the part of the rock that seemed most suitable, i.e. the north-western part of the candidate area. Evaluation and modelling at the completion of the site investigation phase have later showed that the “target area/volume” also contains less suitable regions. This fact has been considered in the repository design and layout work, see Section 5-2 and Figure 5-6 in TR-11-01.

Q 2.3.7 Figure caption: What is the “target volume in the north-western part of the target area”? (P. 111)

This is an editorial error. It should be “target volume in the north-western part of the candidate area”.

Q 2.3.8 Is “Investigation site” the same as “candidate area”? Why the use of two different terms? (P. 109)

Yes. Investigation site in Figure 4-6 is the same as “candidate area” and there is no good reason for using this term. It would have been better with “candidate area” also in Figure 4-6.

Q 2.3.9 Why are the horizontal stresses at Forsmark higher than typical for the Swedish coastline? Is there a clear relationship to the sedimentary loading and erosion history? (P. 116)

Many parts of Sweden had an erosional history similar to Forsmark and we do not think the state of stress at Forsmark can be related solely to its erosional history. However, an uncommon, but not unique, characteristic of Forsmark is the low frequency of open fractures at a relatively shallow depth. The higher the rock mass quality, i.e. the greater the stiffness, the greater the horizontal stress, in keeping with our experience with other crystalline sites. The issue is discussed in SKB R-07-26 from which the figure below stems.

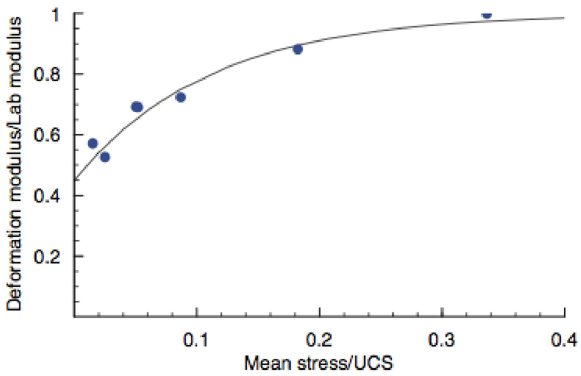


Figure 6–3: *Relationship between mean in-situ stress determined from overcore measurements normalised to the laboratory uniaxial compressive strength (UCS) and rock mass deformation modulus determined from back analyses of deformation measurements and normalised to the laboratory intact Young's modulus.*

Q 2.3.10 Fractures occur on all scales. What is the lower size limit of fractures considered in the discrete fracture network models? Where is this lower limit justified? (P.120)

The lower size limit differs between different modelling approaches. DFN models were produced in which either the lower limit was set to equal the borehole radius (and varying scaling exponent to match measured intensity), or computed by fixing the scaling exponent and varying the lower size to match measured intensity. Details are provided in the Data Report (TR-10-52, section 6.3, p. 236). Further details are provided in R-07-46 (GeoDFN), R-07-48 (HydroDFN) and R-09-20 (HydroDFN realizations).

Q 2.3.11 There seems to be no description of brittle fault rock (cataclasites, gauge, etc.) in the sections describing the mechanical properties of fractures and deformation zones. Do brittle fault rocks really not occur in the Forsmark region? Are all brittle fractures only extensile fractures? Why so? (P. 121)

Most deformation zones at Forsmark display brittle reactivation, expressed as consolidated breccias and cataclasites, of ductile precursors. The kinematics includes strike-slip components on steep zones and reverse-slip components on gently dipping zones. The characteristics of the deformation zones are detailed in the Site Description Forsmark (R-07-45, e.g. Section 3.7, p. 91) and especially its appendix (Appendix 15) which constitutes an important source of information to the assessment.

Q 2.3.12 When comparing the *measured* maximum horizontal stress magnitudes in the target volume with those measured above the A2 deformation zone, can a clear statistically significant difference be shown? Where can an explanation/discussion be found of the large variations per depth interval within the same domain? (P. 124)

A detailed analysis of the stress results from KFM02B and the numerical modelling of the results is given in SKB R-07-31. Based on the measured results for the site combined with the numerical modelling results, we believe there is a significant difference for the stresses above A2 and those below A2.

Q 2.3.13 Where can the detailed discussions be found about when and how fracture hydraulic properties can change in the future (short term, i.e., in response to the excavation, and on geological time scales)? (P.125)

By SKB's definition, future evolution is not part of the site description but is assessed as a part of the safety assessment. In the SR-Site main report this is reported in chapter 10 (sections 10.2.3, 10.3.5 and 10.4.4). The findings presented in the SR-Site main report are all based on the assessment made in SKB TR-10-23. Generally, it is found that most future changes are small and have no or limited impact on risk.

Q 2.3.14 The first paragraph on P. 125 states that there is a poor correlation between *in situ* stress and fracture transmissivity. Is the heterogeneous stress field known well enough to draw such conclusions at the scale of individual fractures? (P. 125)

- **The maximum horizontal stress orientation at Forsmark in the target Volume is quite consistent at all scales: Overcoring, Borehole breakouts, Hydraulic Fracturing, HTPF and integrated HF and HTPF.**
- **The rock mass is sparsely (open) fractured and this fracture frequency decreases with depth. Hence, the rock mass is relatively homogeneous and sparsely fractured in the Target Volume.**
- **We analyzed the correlations between fracture flow and horizontal stress at the individual fracture scale and the Deformation zone scale. At the individual fracture scale there was no significant correlation observed. At the deformation zone scale, the NE fractures that are the most conductive are perpendicular to the maximum horizontal stress. If there were a strong coupling with flow and stress, one would expect these NE Deformations zone to be the least conductive.**
- **There was minor coupling between fracture flow and the vertical (minimum)stress. This was observed in the gently dipping deformation zones, but not the individual discrete fractures.**

The methodology was also applied at Laxemar with similar findings. There, individual boreholes were analyzed where we had both stress measurements and discrete fracture flow measurements in the same borehole.

Q 2.3.15 What are the pieces of hard evidence for the postulated, pronounced regional hydraulic anisotropy? Where are they discussed in detail? (P. 125)

In fractured crystalline rock, it is the differences in the spatial distribution of the 3D intensity of connected open fractures of different sizes in different orientations that creates a regional hydraulic anisotropy. The pieces of hard evidence for a regional hydraulic anisotropy at Forsmark are described in detail in R-07-48 (single borehole scale) and R-07-49 and R-08-23 (cross borehole scale).

Q 2.3.16 What are the reasons to subdivide the target bedrock volume in three, not two, depth intervals for fracture domains? Where is a detailed discussion given? (P. 125)

The reason for a division of the target bedrock into three depth intervals for fracture domains is based on the conductive fracture frequency. The data and the analyses are presented in detail in R-07-48.

Q 2.3.17 What is the test interval length of Figure 4-16 upper inset? (P. 126)

The geological thickness of a deformation zone defines the bounds for the integration of local measurements of borehole transmissivity. That is, the calculation of the deformation zone transmissivity is accomplished by summing up the local T values measured between the intercept boundaries. In the case of PSS data (i.e., packer-test data) the test interval length is 5 m. In the case of PFL data (i.e., flow logging data), the test interval is 0.1 m. The origin and

derivation of transmissivity data shown in this inset is described in R-07-48, which also describes the similarities and differences between PSS data and PFL data.

Q 2.3.18 The cross section of Figure 4-18 includes a thick till layer - which is normally a low permeability soil - overlaying high permeability fractured bedrock. A low permeability layer is also indicated on page 140 (at least vertically). Why does a flow net for such permeability layering not show primarily vertical flow in the aquitard and horizontal flow in the aquifer? Where are the two de-coupled water table levels discussed elsewhere in the text? Should flow lines crossing permeability boundaries not show refraction? (P. 128 & P. 140)

As explained in the figure caption, Figure 4-18 is a cartoon that focuses on the notion of an anisotropic, highly permeable shallow bedrock aquifer. The till layer is relatively thin, on the average c. 3-5 m. In terrestrial areas, the glacial till is affected by post-glacial processes such as abrasion (due to shoreline displacement), seasonal freezing and thawing, and vegetation (e.g. roots). These processes affect the hydraulic conductivity in contrast to the more inert glacial till below the lake sediments. As stated on p. 140, the hydraulic conductivity of the glacial till is significantly anisotropic with K_h=(5 to 20)K_v. Data that support this statement are presented in the site investigation phase, see e.g. R-08-08 and R-08-09. For the sake of comparison, it may be noted that the hydraulic conductivity of the anisotropic, highly permeable shallow bedrock aquifer is associated with thin but extensive sheet joints. The transmissivity of the sheet joint varies in space but local values as high as 1×10^{-3} m^2/s have been observed. Thus the horizontal hydraulic conductivity of the sheet joints is approximately 2-4 orders of magnitude greater than that of the glacial till.
In the general case there are not two water tables at Forsmark. In the 3D flow modelling we have only one water table.

Q 2.3.19 Where can a detailed description and discussion be found of the (high) hydraulic gradients inferred from deep borehole measurements, that exceed topographic gradients? (P. 128)

The statement in TR-11-01 on p. 128 is unfortunately not a proper summary of the original discussion given on p. 289 in TR-08-05. There, it is concluded that different types of errors are incorporated in the inference of deep hydraulic gradients. The reviewer is kindly asked to read the original text. We are happy to discuss this issue further if any additional explanations are needed.

Q 2.3.20 Where can the detailed data sources of Figure 4-22 be found (matrix pore water sampling locations, fracture groundwater sampling locations)? Are the data sources sufficient to characterize the hydrochemical conditions in the "target volume"? (P. 133)

More detailed information regarding data sources and representativity of data is provided in the SKB report R-08-47 and references therein, especially SKB report R-08-105 concerning matrix pore water.

Q 2.3.21 Where can the detailed descriptions be found of the "altered rock surrounding flow paths"? How old are these alterations? (P. 137)

Some additional information on this is provided in Section 4.4.4 in TR-11-01 but more details are given in the report Site description Forsmark (SKB TR-08-05) and references therein. The geological description in Chapter 5 (especially Section 5.2.3) addresses this and fracture mineralogy and alteration are also addressed in Chapters 9 and 10.

The most abundant type of alteration is oxidation which has been associated with hydrothermal fluid movement and thus is an ancient feature (more than c. 1 Ga old).

Q 2.3.22 Where can detailed information be found about borehole hydraulic head measurements, about maps and sections with measured hydraulic heads (and interpolated contour lines), recharge and discharge zones? (P. 140)

Please see the surface hydrogeology report R-08-08.

Q 2.3.23 Where can a detailed description be found of the underground site characterization program? How is this program integrated with the construction activities? (P. 151 & P. 153)

The underground site characterization programme is provided in R-10-08. This document is in Swedish, with a one page English summary. An English translation is expected by the end of October, 2011 (see response to Q 2.8.15). A general account on the integration between Site Characterisation and Underground construction activities is also given in Chapter 3 of the Underground Openings Construction report (SKB TR-10-18).

Generally, the development of the underground facilities is carried out in stages. Initially the accesses to repository depth are developed, followed by the central area and the deposition tunnels and holes for the test operation. Finally, during the routine operation, the repository will be developed in stages.

During each stage deposition works and rock construction works are carried out in parallel on opposite sides of a partition wall. Each stage comprises the construction of deposition tunnels and holes required for a given number of canisters. During each development stage deposition works are carried out in the part of the deposition area completed in the previous stage, and detailed site investigations are performed for the deposition tunnels and holes to be constructed in the next stage. Thus there are three separate activities associated with a stage in the development of deposition areas:

1. **investigation of the detailed site conditions and the adapting of the layout to those conditions,**
2. **construction of deposition tunnels and deposition holes, and**
3. **Deposition works including deposition of canisters and installation of buffer, backfill and plug at the end of deposition tunnels.**

The step-wise development of the deposition areas will enable systematic auditing of the design and construction activities.

Q 2.3.24 Where can detailed descriptions be found of grouting measures and grouting restrictions? (P. 155)

Grouting is discussed in the Underground Openings Construction report (SKB TR-10-18), Sections 4.6.2 and 5.2.4.

Q 2.3.25 Hydrogeological measurements often only refer to small test volumes in comparison to volumes that control long-term inflow to underground excavations. This is one reason why most design methods used to estimate groundwater inflow into underground excavations in fractured rock fail (sometimes catastrophically). Where can detailed descriptions be found of the predictions made for inflow to the KBS-3 repository at Forsmark? (P. 158)

The inflow calculations are presented in report R-09-19.

Q 2.3.26 The statements made about correlations between fracture size and inflow (transmissivity) are surprising. Where can the detailed discussions related to the transmissivity criterion of 1E-6 m^2/s (radius >250 m) be found? Which local geophysical method is capable of detecting every fracture with a radius bigger than 250 m? (P. 158)

The cited section claims that given the assumed correlation between fracture size and transmissivity (which is justified in SDM Site Forsmark), the application of the FPC/EFPC will also imply that the criterion will find many high transmissivity fractures. However, since the correlation between fracture size and transmissivity is uncertain the section argues that it would be preferable to complement this criterion with one that directly addresses fracture transmissivity (regardless of its size) and also discusses to what extent inflows to a deposition hole could be used for such a complementing criterion. We see nothing surprising in that!

Regarding the claim that all fractures larger that 250 m radius and T>10^{-6} m^2/s could be found – it is essentially based on judgments. A large 10^{-6} m^2/s fracture would imply in the order of 10 L/min inflow (if not affected by skin), and will be clearly visible by Ground Penetrating Radar and borehole seismics. Clearly, these judgments need eventually be put on even firmer foundation and demonstration tests are planned in the Äspö HRL as part of the development of the underground characterization program. Furthermore, Posiva in Finland in its DEMO-test, is currently carrying out detailed characterization to be followed by excavation and monitoring. These tests clearly demonstrate that even much less pronounced transmissive fractures can be found prior to excavation of a deposition tunnel.

Q 2.3.27 Where can a discussion be found of the selected excavation method (drill and blast compared to tunnel boring machine)? (P. 159)

**A discussion on different excavation methods can be found in R-04-62 (Choice of rock excavation
methods for the Swedish deep repository for spent nuclear fuel). Drill and Blast is identified as the preferred method primarily due to flexibility and cost. The discussion is continued in RD&D programme 2007 (TR-07-12, sec 12.5) based on results from new experiments at the Äspö HRL.**

Q 2.3.28 In underground excavations of heterogeneous fractured rock, complex hydraulic head gradients might develop which do not need to be uniformly oriented towards the excavation (e.g. deposition borehole) during the initial saturation phase. Could such shortcuts not lead to unexpected erosion of buffer material and clay? (P. 227 ff)

Please see also the response to Q 2.3.25 above. The inflow calculations presented in R-09-19 are based on an up-scaling of the underlying discrete fracture network model using a fine resolution close to the tunnels and deposition holes. Thus, the numerical model incorporates the complex flow behaviour that may result due to the fracture network characteristics. The evaluation against the inflow threshold thus also takes into account these complex flow phenomena.

2.4.1 Questions from IRT Member 4

These questions relate largely to the hydrology of the Forsmark area. The questions are based on TR-11-01.

Q 2.4.1 It is not clear how the flow-dimensions and their spatial distribution are treated in the analysis. For example, according to the analysis of Pipe Strings System (PSS) data, 20 to 30 % of analyzed data suggest their flow-dimension to be close to 1-D, i.e., channeling flow. However, the DFN model and the ECPM model seem not to directly include the channeling flow effect. It might result in a conservative model because fractures tend to be well-connected. On the other hand, correction of transmissivity is necessary in the case where the channeling flow is taken into consideration, and the well-connected fractures approach does not necessarily constitute a conservative model. It would be helpful to receive information on how SKB considers the heterogeneity issue, especially the effect of the flow-dimension, and how it propagates to the safety discussion.

As explained in the Data report (TR-10-52, Section 6.6.7), the PSS tests are conducted for a very limited time period (1200 s) in contrast to the PFL tests (several days). This difference together with other methodological differences (see TR-10-52, Section 6.6.7 or Section 4.3 in R-07-48 for details) imply that the PSS method cannot readily distinguish between isolated (compartmentalised) and connected clusters of fractures. The low flow-dimensionality is often shown to be followed by "negative hydraulic boundary", see Section 4.3 in R-07-48 (in particular Figure 4-17). This implies that the flow dimensionality in hydraulic testing varies with test time.

Concerning channelling, it is noted that the main mechanism causing channelling is the fracture-to-fracture variability in a sparse network; this effect is incorporated in the DFN model (and partially also in the up-scaled ECPM model). However, channelling due to internal fracture variability is neglected; the reasons for this model simplification are given in the Radionuclide Transport report (TR-10-50, Section 2.1.1 and Appendix A) and in the Data report (TR-10-51, Section 6.7.6. The methodology used to derive hydraulic properties of an interconnected network of flowing fractures is described in R-07-48 (Chapters 10 and 11) and in TR-10-52 (Section 6.6.7).

Q 2.4.2 Similarly, how does the uncertainty on the fracture-size distribution of the bedrock affect the results such as the numbers of the loss of deposition holes, the values of Q1 through Q3, and the F-factor? Also, it would be helpful if SKB provided their strategy to reduce the uncertainty by future survey in the area.

The decision to use a power-law fracture-size distribution in the hydrogeological DFN modelling is in accordance with the geological DFN modelling. That is, the two DFN models are compatible since the fractures of the hydrogeological DFN are a subset of the fractures of the geological DFN. The uncertainty resulting from the calibrated model parameters (derived in R-07-48) is tested in SR-Site by means of multiple realisations of the given distribution with the results being propagated for further analysis.

During the detailed phase investigations (underground investigations), more data on specifically small fractures will be obtained. This will provide an opportunity to assess the power-law assumption of the geological DFN model.

Q 2.4.3 The reasons for choosing three correlation models between fracture size and transmissivity are not clear. Only qualitative reasoning is shown. It is understood that a quantitative discussion for this kind of model is difficult; however, it is desirable to know how and why SKB chose three models, i.e., full correlation, no correlation, and semi-correlation, for the analysis.

The work resulting in the three correlation models is presented in detail in R-07-48. In short, the fully correlated and uncorrelated models are assumed to be bounding models, whereas the semi-correlated model represents a more realistic description of the likely correlation between fracture size and transmissivity. Since SR-Site judged it impossible to fully argue for one single correlation model based on the results available, all three correlation models are propagated through the analysis. It is noted that in the calibration presented in R-07-48, all three hydrogeological DFN models derived (i.e., the three different correlation models) could reproduce the data.

Q 2.4.4 It is not clear how the criterion for the discharge to the deposition holes, i.e., less than 0.1

L/min., was determined.

The actual number is somewhat arbitrary but should be low enough to really imply an improved safety, without being overly pessimistic such that many actually suitable deposition holes would be discarded. For this reason, the adequacy of any number eventually used as a design premise need be tested to ensure that it is sufficiently effective. Preliminary such tests suggests (see section 14.3.2 p 765) "*that avoiding inflows above 0.1 L/min implies that Darcy fluxes above 10^{-2} m/yr during saturated temperate conditions would not occur. To further study the potential effects of such a criterion, the identified deposition positions with high inflow rates under open repository conditions were omitted in an analysis of the central corrosion variant of the corrosion scenario, for the base case realisation of the semi-correlated hydro-DFN model. This led to the result that no canister failures occurred in the scenario, i.e. all the unsuitable deposition positions were identified by this procedure*". Further and more elaborate tests are planned – see section 15.5.13 of SR-Site Main report).

Regarding the initial choice of 0.1 L/min as a potentially suitable number there are essentially two different origins:

The main reason is the correlation between inflow and the transmissivity of fractures intersecting a deposition hole. Discarding skin effects, 0.1 L/min inflow would require an intersecting fracture of $T=3 \cdot 10^{-9}$ m^2/s, which in turn would imply a relatively low Qeq and a relatively high F-value for saturated conditions.

Another reason concerns the potential for mitigate piping/erosion where it previously was thought (SR-Can Main report /SKB 2006a, section 9.2.4/) that inflows below 0.1 L/min would not be a problem 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.

Q 2.4.5 The numbers of deterministically treated fracture zones are different between the local and regional models. Is there any reason for this? And, how was the effect of this change evaluated? Also, how did SKB define the size of deterministically treated fracture zones to be longer than 1,000 m?

The number of deterministic structures defined within a model volume is steered by the size of the model volume and the lower truncation level set by modelling policy. The overall ambition was to maintain model resolution throughout the entire model volumes, and to treat structures smaller than the lower truncation levels stochastically. In the regional model, a side length of 3000 m was judged adequate to handle a manageable number of deterministic zones. In the local model volume, the truncation level was set to 1000 m.

Q 2.4.6 Are the total head distributions from measurements using deep boreholes and the model result consistent? It seems that some discrepancy exists between the measured data and the calculated results, especially in the deeper part.

Please see the response to Q 2.3.19.

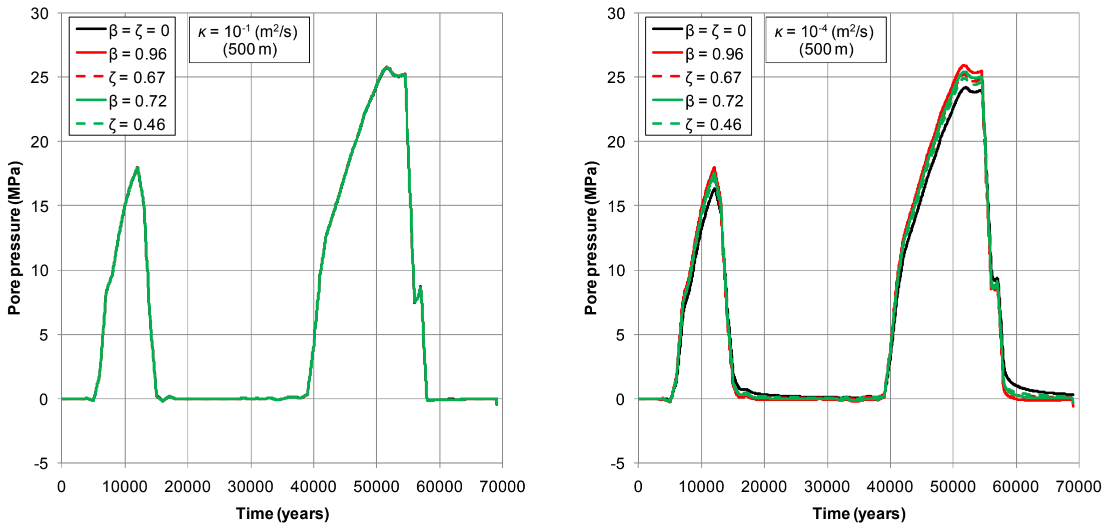
Q 2.4.7 In relation to the question 2.4.6, it is not clear whether the treatment of the pore pressure for the mechanical analysis and the groundwater flow analysis is consistent. For the mechanical analysis, a simple hydrostatic pore pressure increase by ice loading is considered; however, mechanical loading and the change of recharge amount/discharge location should affect groundwater flow, and hence, pore pressure distribution. Especially if the hydraulic conductivity of the formation is quite low, the loading/unloading-induced pore pressure effects could be important. It would be necessary to argue the consistency between the mechanical and hydrogeological analysis for long-term processes. In other words, how are the mechanical/fluid flow coupling processes by ice-mass loading/unloading taken into account? And how is the effect evaluated?

For the mechanical analyses the priority has been to ensure that the stability of the repository rock mass is not overestimated at any time. Therefore, the hydrostatic pore pressure increase caused by the ice load has systematically been assumed to be the highest possible given the height of the ice, i.e. regardless of any projected changes in recharge/discharge amounts/locations and any associated variations in pore pressure distribution.

The hydro-mechanical coupling is ignored. The effect of ignoring that coupling is assessed in SKB R-09-35 (Appendix A, pp. 80-84) using 1D analytical solutions assuming the ice sheet to be warm-based at all times (i.e. in keeping with the maximum hydrostatic pore pressure approach explained above).
Results from three modelling approaches are compared:

- **Mechanically uncoupled solutions**
- **Mechanically coupled solutions assuming that the ice load does not induce any horizontal strain**
- **Mechanically coupled solutions accounting for the mean total glacially induced stress in the reference glacial scenario SKB TR-09-15**

For high values of the hydraulic diffusivity, the mechanical coupling effect can be ignored (Figure 1, left column). For low values of the hydraulic diffusivity mechanical coupling does have an effect on the pore pressure at large depths, but practically none at repository depth (Figure 1, right column). Considering that the potential for mechanical instability of fractures is greatest following a de-glaciation and that results from the coupled 1D-analyses show that the pore pressure is reduced more quickly during a de-glaciation than in the uncoupled analyses, it is concluded that it is effectively conservative and therefore justified to ignore the coupling (even if the stability is overestimated at large depths during high stability periods). It should also be noted that the impact of the glacially-induced excess pore pressure on the stability decreases with depth.



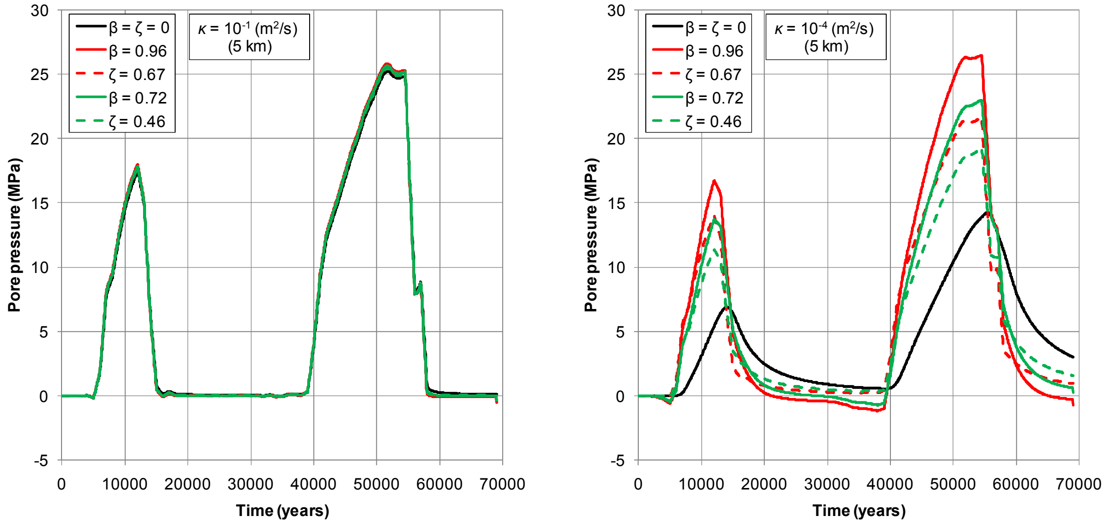


Figure 1. Temporal development of the pore pressures at 500 m (top) and 5 km (bottom) depth for different values of the hydraulic diffusivity – 10^{-1} m^2/s (left column) and 10^{-4} m^2/s (right column). β = ζ = 0 represents the uncoupled solution, whereas β = 0.96 or 0.72 are results from mechanically coupled analyses accounting for the mean total stress and ζ = 0.67 or 0.46 are results from mechanically coupled analyses assuming that the ice load does not induce any lateral strain (β and ζ are the 3D and 1D loading efficiencies, respectively). From SKB R-09-35 Fig A-6, p. 83.

Q 2.4.8 The interference test results are used to validate the model used in this study. However, the spatial scales for the test and the discretization of the model may be different. How is this scale issue treated for validation purposes?

The scale of the grid elements was mostly around 25 m. The scale of the borehole monitoring distribution was up to 2 km, and so there were generally tens of elements between the pumping borehole and the monitoring boreholes. As an example, please see R-08-23, Section 5.3.1 and the simulation of the interference test conducted in HFM14.

Q 2.4.9 For long-term safety analysis, information on the east/northeast of the candidate site may be necessary. What is the status on the acquisition of sub-sea information? And how does SKB evaluate the uncertainty of these data on the results of their analysis?

The investigations of the sea area include airborne geophysics (e.g. magnetics), sonar data which provide information on bottom surface topography and sea bottom sediments. Combined, these data provide information on major deterministic deformations zones and potential future discharge points. The repository volume is bounded by the major Singö and Forsmark deformation zones which, to a certain degree, tend to constrain the groundwater flow within the tectonic lens.

In order to investigate the effect of detailed data being available from outside of the lens, a model variant was conducted in R-09-20 (Sections 5.4 and 6.3.4) where recently obtained fracture data from the SFR (repository for low and intermediate level waste just outside of the lens) site was assumed valid for the full regional scale domain outside of the lens (i.e., outside of the HRD volumes used in SDM-Site and SR-Site otherwise).

Q 2.4.10 Is the model scale appropriate for analyzing recharge/discharge locations? The obtained discharge locations seem to be very close to the model boundary, and hence, they might be affected by the boundary conditions of the model.

It is argued that the model size in the temperate hydrogeological simulations is appropriate for

present day conditions; i.e., recharge and discharge locations are well captured. For future times, (parts of the) discharge from the repository is close to the model boundary. However, it is argued in SR-Site that this has only a marginal effect on the definition of biosphere objects. Also, it is noted that climate will change around the time when discharge becomes close to the boundary, and hence the periglacial/glacial hydrogeological model becomes more appropriate for describing groundwater flow at the site.

Q 2.4.11 For the discussion of several glacial cycles, is it appropriate to simply repeat the processes? Can all the processes, e.g., distribution of groundwater chemistry, be considered to become the same after one cycle of glacial cycle? Is there any supporting evidence?

The approach of repeating glacial cycles is based on a conceptual model that takes groundwater chemistry data and results from numerical groundwater flow simulations into account.

The chemical composition data and the resulting groundwater site model are summarised in section 4.8, subsection "Groundwater in fractures", page 132, and a full description of the present-day hydrogeochemistry of the site is given in R-08-47. The evidence from the groundwater compositions obtained during the site investigation suggests the following. In the candidate repository volume, FFM01 (see Fig.4-19, upper), brackish marine groundwaters (Littorina and last deglaciation components) are absent below 300 m. Fig 4-22 in SR-Site's main report illustrates this, but a better explanation is found in Figures 6-1 to 6-3 in R-08-47. The groundwater data indicates low-flow to stagnant groundwater conditions with increasing depth within the repository footprint. It is to be noted that the hydrogeochemical model includes, at repository depths, a meteoric-glacial component *older* than the last glaciation, see report R-08-47, sections 1.3, 2.5. The site investigation concluded that glacial melt waters from the last deglaciation did not penetrate to depths greater than 100-200 m at Forsmark, see section 7.3.3 in R-09-47.

The present situation with fracture groundwaters showing that there has been practically no influence of either the last glaciation or of the last Littorina period within the repository volume (below 300 m depth within the repository footprint) indicates that this rock volume is not very sensitive to the surface conditions during a glacial cycle. However, the evidence for an older glacial component indicates that the possibility of a future glacial meltwater penetration can not be fully excluded.

The numerical flow simulation model is pessimistic in its boundary conditions and in its propagation of hydraulic pressure to depth. Even so, the results show that after a glacial cycle groundwater salinities are mostly recovered (see Figs. 10-134 and 10-150).

The present situation in Forsmark reflects many past glaciations cycles, and the numerical simulations and the present day groundwater data suggest that oscillations in salinity at repository depth, if present, level out.

It must also be noted that the repetition of glacial cycles is just postulated in the reference evolution of SR-Site, but that the consequences of other evolutions are later addressed within the different scenarios analysed in chapters 12 and 13.

Q 2.4.12 For the calculation of F-factors by the particle tracking approach, it seems that the rejection of deposition holes by FPC and/or EFPC criteria is not taken into account. It would be helpful if SKB explains the reasons for this apparent inconsistency.

In the hydrogeological simulations, all deposition hole positions are included in the analysis (including particle tracking) and also in the majority of figures shown. However, the FPC and EFPC positions are also identified in these simulations. Thus, in some figures the FPC/EFPC

positions are excluded, and in the SR-Site base case for further analyses the FPC/EFPC positions are also excluded.

2.5 Questions from IRT Member 5

2.5.1 Reference scenario, initial state

Canister and insert

Q 2.5.1 SKB recognizes that the canister and the insert have to meet the rigorous design premises (e.g. Vol. 2 p. 435, Vol. 3 p 766, p. 817, p.822). How is the quality of production assured? Are non-destructive testing methods available? What are the consequences if the required quality cannot be assured?

This answer is a response both for Q 2.5.1 and Q 2.8.1.

The manufacturing process, including the quality controls, will be qualified under supervision of an authorized body. Development of non-destructive testing methods at the Canister Laboratory is ongoing in parallel to the development of the detailed acceptance criteria. The first version of the NDT methods has therefore been developed based on preliminary criteria. In order to evaluate the capability of the methods, full-scale inspections have been performed and the results have been used to identify needs for further development /TR-10-14 section 5.2-5.5 and SKBDoc no. 1179633/.

If the required quality for a specific part of the canister cannot be assured, the part will be rejected.

Q 2.5.2 SKB states that: "given the technical challenges in meeting the rigorous requirements and NDT capability, it might be considered appropriate to relax the requirements for the canister…" (Vol. 3 p. 822). Does SKB plan to change the design premises? What consequences may be expected?

We are currently exploring the potential for revising the design premises moving from the current deterministic rule to a probabilistic one. This would allow for a more realistic description of the potential defects of the cast iron insert and the spatial distribution of the buffer material. This potential change of design premise will only be made if we can prove that safety is not affected. The changes would primarily not change the reference design but would lead to more adequate testing and control procedures of the buffer and canister.

Q 2.5.3 Statements on the initial state of the canister and the insert and their development on the long term are based on analysis of BWR canister and inserts. PWR canister and inserts are considered to be more robust and SKB assumes that they will meet the requirements if the BWR meets them (Vol. 1 p.175). Has SKB actually analysed this? Where is it documented? Is it planned to later include analysis of PWR?

SKB has performed damage tolerance analyses for the isostatic load case for both the BWR and PWR insert. The results show that the insert withstands loads more than twice of the design load. The analysis of the PWR insert has though been performed without the use of verified material data. For the rock shear case SKB has performed damage analyses mostly for the BWR insert (one PWR case). The results show that the insert withstand the loads. However, as the margin is relatively small it set rather high requirements of acceptable defect sizes in the insert. /TR-10-14 chapter 4/.

SKB is currently carrying out complementary analyses for the PWR type for both the isostatic and the rock shear loads case.

Buffer, backfill, plug

Q 2.5.4 According to SKB the deposited buffer density and the composition of the buffer and the backfill are among the most important safety related features (Vol. 1 p.22). SKB concludes that in order to assure the sealing abilities of the plug and the bentonite an aperture smaller than 5 μm in the contact zone between the concrete plug and the rock surface is required (Vol. 2 p.304). SKB further recognizes that it is not known how tight the plugs can be made (Vol. 2 p.306). How is it assured that the buffer, the backfill and the plug will meet the design premises? How is it tested?

It is stated that an aperture smaller than 5 μm in the contact zone is needed, if no credit is taken for the clay seal in the plug. The contribution of the clay is most likely significant. The uncertainties about the plug on page 304 and 306 are related to the fact that the plug design is not yet finalized. A full scale test of a plug with a clay seal is planned at the Äspö HRL, as further described in the response to Q 2.8.2.

The sealing ability of the plug is only needed during the operational period of the repository. No sealing ability is needed, when the main and transport tunnels have been backfilled. This means that the sealing ability of the plugs can be monitored for their entire service life.

Deposition hole acceptance criterion EFPC

Q 2.5.5 According to SKB the acceptance of deposition hole according to the established EFPC criteria is one of the most important safety related issues (Vol. 1 p. 22). SKB recognizes as well that it is important to continue the development of acceptance criteria.
How is the successful application of EFPC assured? Has the successful application been tested? What are the consequences if not all existing water-bearing fractures are detected when applying EFPC? How many fractures could experience advective conditions without jeopardizing the safety? What are the consequences if more than the assumed water-bearing fractures will be detected?

The successful application of the FPI criteria (FPC and EFPC) underground, essentially only requires an ability of the geologist to detect the fractures by visual inspection, using standard mapping routines. As mentioned in the SR-Site main report, p. 473, 767, and elaborately argued for in SKB R-06-39, large fractures are indeed not geophysically, hydraulically or geochemically anonymous as conservatively assumed in the assessment (se also answer to question 2.8.7). The traditional geological mapping will be complemented by an array of investigation techniques, procedures of which will be detailed as the ongoing programme for detailed underground mapping is completed. SKB plans to test and develop the mapping methodology at the Äspö laboratory and to fine-tune the methodology during the excavation of the access tunnels at Forsmark. Additionally, SKB is currently cooperating with Posiva on certain aspects of the EFPC utilising experiences gained from the ongoing excavations at Onkalo.

When applying the EFPC, all existing water-bearing fractures are not expected to be detected. In fact, most of the deposition holes intersected by water-conducting fractures will be accepted by the EFPC, which is only a geometrical criterion, serving as a proxy for fracture size. However, many of the largest fractures are also expected to be among those with the highest volumetric flow, meaning that the high-end tail of the flow distribution will be reduced for the set of deposition holes remaining after application of EFPC. Furthermore, considering that this reduction partly is a consequence of the somewhat uncertain correlation between fracture size and transmissivity we also suggest a complementation of the EFPC with an inflow criterion (see

p. 828). Such an update is now actually being considered in the ongoing work for revising the design premises.
The calculated consequences and risk are thus those obtained with the imperfect reduction of flowing fractures obtained through application of the EFPC.

A sensitivity case exploring the effect of not applying any rejection criterion is presented in section 14.3.2 of the SR-Site main report, yielding an increase in the number of failed canisters of about a factor of 30 (section 14.3.2) and a similar increase in calculated risk (see the Radionuclide transport report, TR-10-50, section 4.8).

The bounding case of the corrosion scenario in the risk summation is one where all deposition holes are pessimistically experiencing advective conditions initially. Thus, the bounding risk curve is one where all accepted deposition positions are experiencing advective conditions, and in which case safety is upheld. This is due to the longevity of the canister for the favourable hydraulic and geochemical conditions at the Forsmark site.

The consequences of better-than-assumed rejection of water bearing fractures are to some extent explored in section 14.3.2, where e.g. the following is stated on p 764: "*This means that if deposition positions with long term Darcy fluxes of 0.001 m/yr or more could be identified and rejected, then the risk over the one million year assessment time associated with the corrosion scenario should vanish. It is also noteworthy that a Darcy flux limit of 0.01 m/yr would not reduce the risk much compared to what is obtained with the EPFC criterion, since almost all of the few positions with such Darcy fluxes are already avoided.*"

The above response also covers Q 2.5.25. It also relates to Q 2.5.6.

2.5.2 Long term performance

Advective conditions/EFPC

Q 2.5.6 In its assessment, SKB makes several assumptions concerning the occurrence of water-bearing fractures and advective conditions in the buffer with regard to application of EFPC. In the reference scenario it is assumed that "roughly 70% of deposition holes do not have a flowing fracture intersecting the deposition hole" (Vol. 2 p.346). This is assured due to application of the deposition acceptance criterion EFPC. It is further assumed that: "No deposition holes are expected to reach advective conditions during initial temperate period (Vol. 2 p. 434); " Up to 2% of deposition holes may experience dilute conditions during a glacial cycle, only one deposition hole is calculated to lose buffer mass"(Vol. 2 p.537); and "Even for the most unfavourable cases less than 10% of the deposition holes reach advective conditions (Vol. 3 p.580). How many fractures may have advective conditions without jeopardizing the safety?

The fact that roughly 70% of the deposition holes are not intersected by a flowing fracture is due to the low frequency of water bearing fractures at Forsmark, and not due to the application of EFPC. This figure would be almost unchanged if no EFPC rejection would be assumed.

Regarding the number of deposition holes that may experience advective conditions in the buffer volume without jeopardizing safety, the answer is given in the response to Q 2.5.5 (i.e. all deposition holes are in fact assumed to experience advective conditions in the bounding case of the corrosion scenario used in the risk summation).

Transport resistance

Q 2.5.7 SKB assumes that 90% of all potential deposition holes have F-Values above 10^6 y/m (Vol. 2 p.430).The transport resistance has been characterised as one of the input variables having the most impact on the dose calculation (Vol. 3 p.690).Which F-Values are possible without jeopardizing the safety?

Comparing Figure 13-39 (near-field releases for the corrosion scenario) to Figure 13-40 (far-field releases for the corrosion scenario), shows that even with the extreme and hypothetical assumption of no geosphere retention (i.e. F = 0) yields an increase in dose by about an order of magnitude. Since the margin to the risk limit in the risk summation is about an order of magnitude at the peak risk occurring at one million years for the corrosion scenario, this suggests that safety, in the sense of compliance with the risk criterion, can be demonstrated even without geosphere retention for the corrosion scenario. (For the other risk contributing scenario, the shear load scenario, pessimistically no geosphere retention is assumed.)

Colloid formation/ Buffer erosion

Q 2.5.8 SKB recognizes that the buffer colloid release/erosion process is poorly understood (Vol. 3 p.575) and that there is a conceptual uncertainty in the erosion model (Vol. 3 p.577). SKB also states that several safety functions cannot be guaranteed for deposition holes that have experienced loss of buffer due to erosion/colloid release to the extent that advective conditions prevail (Vol. 2 p.541 ff). How does SKB plan to fill the knowledge gap and reduce the associated uncertainties? Is the assessment made by SKB on the safe side?

SKB do have an extensive R&D program on the issues of colloid formation and erosion. This is mentioned in section 15.7.3 of the SR-Site main report an presented further in the 2010 R&D program /SKB TR-10-63/.

The risk assessment includes a case where it is assumed that advection prevails initially in all deposition holes. This case gives an upper bound on the consequences of the buffer colloid release/erosion process.

Q 2.5.9 SKB states that "about 100 kg of dry bentonite may be lost due to erosion without jeopardizing the function of the buffer. This situation is handled by avoiding deposition holes with too high an inflow…and is not further assessed in SR-Site" (Vol. 2 p.318). SKB concludes that "no deposition hole will lose so much buffer that advective conditions must be assumed" (Vol. 2 p.435). How much bentonite could be lost in case the application of EFPC is not successful?

The loss of buffer material due to piping/erosion shortly after deposition is not dependent on the EFPC, but on the application of a restriction on how much of inflow to the deposition hole could be accepted during the construction/operation phase. These inflows are easy to measure, e.g. by inspection of how much the water table will rise in a drilled deposition hole if not being pumped. In fact, avoiding such "high" inflow deposition holes may also work as a complement to the EFPC for also avoiding high Darcy flows during the saturated phase, as is further discussed in section 15.5.13.

Backfill erosion

Q 2.5.10 SKB states that "a redistribution of 1,640 kg is assessed to have no impact at all on the backfill performance" (Vol. 2 p. 306). How much backfill could be redistributed at maximum without jeopardizing the safety?

Loss of backfill is treated in section 10.3.9. According to Table 10-5, a few hundred tonnes could be lost.

Plug

Q 2.5.11 SKB states that a failed plug performance is not assessed (Vol. 2 p.306).
Does this have any negative impacts on the dose and risk calculation? SKB notes that the loss of eroded bentonite in the plug is based on an empirical model (p.309). Is this assumed to be sufficient?

The performance of the plug is only needed during the operational period. It has been assumed that failed plugs will be repaired. See also the response to Q 2.5.4.
The empirical model is assumed to be sufficient, since this type of erosion only occurs over relatively short time frames. See also the response to Q 2.1.6.

Copper Corrosion

Q 2.5.12 There have been concerns recently (e.g. from KTH) about the possible corrosion rates of copper under repository conditions, esp. induced by different sulphur compounds that are not addressed in the SKB assessment. Is there evidence that these processes can be reasonably excluded from the safety assessment?

In the corrosion analyses in SR-Site the different sources of sulphide are considered (as described in section 10.3.13 and in the Corrosion calculation report SKB TR-10-66). Sulphide (in its different protonated forms) is the dominating sulphur species in the repository environment, and it has pessimistically been assumed that all sulphide reacts immediately as it reaches the copper canisters. Sulphide written by letters in SR-Site include the different protonated forms (S^{2-}, HS^- and H_2S). In a recent report /MacDonald and Sharifi-Asl, 2011/, that may be the one referred to in the question, the possibility that polysulphides could activate (corrode) copper is discussed, but the report also states that sulphides are present in sufficiently high concentrations that they will activate copper and that the corrosion rate is determined by the transport resistance of the barriers. The pessimistic approach used by SKB is thus covering corrosion also by other forms of sulphur in non-dominating concentrations.

Added reference: MacDonald D and Sharifi-Asl S, Is copper Immune to Corrosion When in Contact With Water and Aqueous Solutions?, SSM Report 2011:09, Swedish Radiation Safety Authority, 2011.

Sulphide concentration

Q 2.5.13 SKB states that there is a large uncertainty in distribution of sulphide which has impact on the copper corrosion, e.g. SKB observes high sulphide concentrations in some boreholes without knowing why this occurs only in some of the monitored sections (Vol. 2 p.360. p.367). How does SKB plan to fill the knowledge gap and associated uncertainties?

Several lines of investigation were started. A report, P-10-18, is being published and a printer's proof may be delivered on request. This report describes a study performed in borehole sections at Laxemar and at Äspö. Further experiments were performed in borehole sections in the Äspö tunnel, and these data are being processed. The collection of additional data on gaseous components and sulphide minerals is being planned. The results of the studies performed so far show that an anomalous sulphide production appears to occur within the borehole sections, tubing, etc. The groundwater monitoring procedures at Forsmark have been adjusted in the light of these results.

Fuel dissolution rate

Q 2.5.14 Although the fuel dissolution rate is considered to have a high impact on the dose calculations (Vol. 3 p.690), the documentation concerning the fuel dissolution in SKB main document is limited. What impacts cause changes in the dissolution rate? Has SKB done any calculation with varying dissolution rates? Where are they documented?

In the main report the fuel dissolution rate is discussed mainly in section 13.5.5 p. 661-666. More detailed discussions are presented in the Fuel and canister process report (SKB TR 10-46, section 2.5.5) and Data Report (SKB TR-10-52, section 3.3). In these documents the impact of intrinsic factors (such as fuel burn-up) and external conditions (such as redox conditions and groundwater composition) are discussed in detail. The calculations have been carried out with a triangular distribution of dissolution rates and are documented also in the Radionuclide transport report (SKB TR 10-50).

Solubility

Q 2.5.15 SKB states that "many of the most hazardous radionuclides have a very low solubility in groundwater and thereby have a limited potential for outward transport" (Vol. 1 p.61). How has the solubility of radionuclides been determined? Where is this discussed/documented? Which values have been used in the model?

Radionuclide solubilities and their speciation in groundwater are discussed in more detail in the Fuel and Canister Process report (SKB TR 10-46, section 2.5.7) and Data Report (SKB TR-10-52, section 3.4). The values used in the modelling are discussed also in the Radionuclide transport report (SKB TR-10-50, Appendix F)

Biosphere

Q 2.5.16 In the biosphere model the distribution of vegetation and land use is modelled. The biosphere model has a spatial detail of 20x20 m (Vol. 3 p. 631). SKB states that "…site representative values were used for model parameters, and their uncertainties were not handled pessimistically…" (Vol. 3 p.645). How is this considered in the dose and risk calculation? Which consequences on the long term are possible due to changes in the model? What are the parameters having the most impact? How sensitive is the Biosphere model to variable radionuclide source terms?

The effect of global parameter uncertainties on the landscape dose conversion factors (LDFs) were assessed by probabilistic simulations (Figure 13-11 Vol. 3 p. 642). From these simulations it was concluded that "*there is a reasonable agreement between the deterministic approach to calculate LDFs [using site representative values] for use in the safety assessment, and a probabilistic approach that propagates parameter uncertainties...*" The uncertainty assessment covers a simulation period of approximately 20,000 years. The upper bound for the effect of not accounting for the biosphere parameter uncertainties are an under estimation of dose by a factor of three (as deduced from the dose dominant radionuclide Ra-226, Figure 13-11 Vol. 3 p. 642). However, this effect is balanced by the treatment of model and system uncertainties, (including the definition of the most exposed group), and taken together quantified uncertainty is not considered to have any significant impact on the assessment endpoints (Vol. 3 p. 645, ending paragraph, details provided in Biosphere synthesis report, p 148-149, Figure 12-9). The parameter that have the greatest impact on LDF uncertainty are K_d and CR (Vol. 3 p. 645) and in the case for Ra-226 well capacity (Biosphere synthesis report p 146-147, Figure 12-8). The sensitivity of the biosphere model to a variable source term has not been directly assessed as the unit release approach was seen as an acceptable approximation for long term assessment of near

steady state conditions. "*This simplified approach is possible since the release from the fuel matrix and corroded metals in the repository are in most cases approximately constant on the time scale of the biosphere assessment*" (Vol. 3 p. 631). However, the effect of the alternative, and perhaps equally likely, scenario that a unit release would reach the biosphere only during the terrestrial stage was examined (biosphere synthesis report p 134, Figure 12-1). The simulation showed that the assumption that the release reached the object all of the simulation time is conservative (with a factor between 2 and 14) for most of the examined radionuclides.

Reference glacial cycle

Q 2.5.17 SKB has chosen a Weichselian type glacial cycle as the reference to assess the effects of future climate evolution, thus repeating the last glaciation cycle (Vol 2, p.287). The maximum known glaciation during the Quaternary has occurred during Saale and/or Elster Glaciations. Ice sheet thickness during Weichselian at the site is supposed to have been 2900 m, while the Saale ice sheet thickness is estimated to have been 3400 m (Vol. 3 p. 612). What is the reason why SKB focused on the comparably lesser glaciation during the Weichselian? Is it unlikely that the next glaciation will be of Saale- or Elster-type? What are the expectable effects of a Saale- or Elster type glaciation?

Since the Weichselian glaciation is the glaciation we have most information from, SKB uses it as a *starting point* for the analysis (by employing it in the reference evolution). However, this does *not* mean that the analyses of all subsequent, complementary, climate cases and corresponding safety assessment scenarios are less important. The complementary cases may often constitute bounding cases with a larger impact on the repository than the reference evolution. In this particular case, the complementary climate case *Maximum ice sheet configuration* (see Climate report section 5.4) is used in the safety assessment scenario *Canister failure due to isostatic load* (Main report section 12.7) to investigate the effect of a Saalian type of glaciation on the maximum hydrostatic pressure. The expected effects of a Saalian type of glaciation is described in Section 12.7 and also below in the response to Q 2.5.20.

Duration of climate periods

Q 2.5.18 Each interglacial is defined for 20,000 years (Vol. 2 p.319). Table 13-7 (Vol. 3 p. 676) shows the duration of each climate period in the simplified 120,000 year cycle.
What are the uncertainties of these assumptions, e.g., concerning the availability of agricultural areas? How are the uncertainties treated in the calculations? Which consequences would changes in the duration of the climate periods have on the calculated dose and risk?

The uncertainties in the duration of interglacial climate conditions are discussed in the climate report section 4.5.4, where it is stated that this uncertainty is large. Alternative durations are treated in the *global warming* and *extended global warming* climate cases.

In the biosphere calculations (LDFs) the uncertainty of the length of the interglacial has been dealt with by an alternative simulation, where the temperate climate conditions have been extended with 50,000 years (corresponding to the *extended global warming climate case*) (Vol. 3 p. 637 first paragraph). For these simulations it has been assumed that radionuclides can continue to accumulate in wetlands for an additional 50,000 years, and that wetlands can be drained and cultivated at the worst possible time during the extended simulation period. The results from these simulations are presented and discussed in Vol. 3 p. 638 (Figure 13-7, and last paragraph). In brief, most radionuclides, including those that dominates dose to humans and other organisms, have reached steady state within the first 20,000 years of the simulation, and thus an extension of temperate conditions has no significant effect on calculated dose and risk.

Permafrost/repository depth

Q 2.5.19 Freezing of the buffer is ruled out for the reference scenario (Vol. 1 p.40). SKB concludes that permafrost will not reach the repository depth neither in the reference scenario nor in the most severe permafrost case (Vol. 3 p.592). The influence of climate and especially glacial conditions is discussed in terms of changes in hydrogeology and hydrochemistry, permafrost-influence, modifications of rock stresses and isostatic load on the container at repository depth. With respect to permafrost conditions, SKB states that "given that the uncertainty in the maximum depth of perennially frozen ground does not reach 450 m depth even in this most extreme unrealistic combination of all uncertainties, freezing of groundwater at repository depth is excluded in the reference glacial cycle." (Vol. 2, p. 447). Has SKB taken into account that the repository depth initially ranging from approx. 470 to 457 m (Vol. 1, p. 151) will not be preserved during its post closure evolution, as the Forsmark Site is expected to undergo further postglacial uplift in the range of approximately 70 m before the next glacial cycle (Vol. 2, p. 444)? How is a repetition of glaciation cycles (followed by depression and uplift and associated erosion phenomena) thought to affect the repository depth? Is there evidence that favourable conditions (e.g. Vol. 2, p. 540, 541) are preserved throughout the assessment period if a gradual reduction of repository depth with time is included?

Although the remaining post glacial uplift is in the order of 70 m, this does not mean that there would be a corresponding surface denudation of 70 m before the next glacial cycle. Interglacial denudation rates over low relief terrain, such as in Forsmark, are considerably lower, see the Climate report section 3.5.4 to 3.5.6. The total denudation (e.g. including glacial erosion) has been estimated to up to 2.6 m for a 100 kyr time perspective, which is negligible in terms of permafrost depths. The erosion by repeated glacial cycles is discussed in the Climate report, section 3.5.4 and references therein. The conclusion is that the total denudation in a 1 Ma time perspective (8 glacial cycles) amounts to 8-21 m at the repository site in Forsmark. In general, the low amount of erosion is a result of the low topographic relief and the fact that the repository is not located in a major fracture zone (more prone to glacial erosion). It should also be noted that the glacial isostatic depression and uplift of the site are not major processes of importance for this erosion (as suggested in the question). The gradual reduction in repository depth is considered to be restricted, as discussed in the Climate report, sections 3.5.4 to 3.5.6.

Isostatic load

Q 2.5.20 Canister failure due to isostatic load is not included in the reference scenario since peak loads in the reference scenario (43.5 MPa) are below the design load of the canister (45 MPa) (Vol. 2, p. 530). The safety margin is not very high. Which consequences are expected if a more severe glaciation, e.g., comparable to Saalian is considered? This would add 4 MPa to the maximum isostatic load (Vol. 3, p. 614), resulting in a value of 47.5 MPa, which is above the canister design load.

It is true that the margin between the reference scenario peak load and the design load is not very large, but as summarised in section 5.4.3 there is a substantial margin in the collapse load in the analyses of the manufactured canister compared to the design load. As described in the Design analysis of the canister (SKB TR-10-28) the failure criteria are calculated using conventional safety factors, like 1.5 for the collapse load compared to the design load. Also, SKB has performed pressure tests on two mock-up canisters /SKB-TR-10-14, SKB TR-05-18/. These tests show that the collapse load for the canister is approximately 100 MPa or higher, i.e. at a load level of more than twice the design load.

Section 5.4.3 is built on the report "Design, production and initial state of the canister" (SKB TR-10-14) and its supporting documents. Section 12.7 in SR-Site is analysing the scenario of

canister failure due to isostatic load, including a thicker ice sheet. In section 12.7.5 it is concluded that the high collapse load gives ample margins also for the most extreme ice load situations.

Global warming variant

Q 2.5.21 Safety function indicators are considered to be similar to the ones of the initial temperate period. Therefore no detail account… is given" (Vol. 2 p.548). During a prolonged temperate period, higher erosion may occur. Has SKB considered this in the assessment?

Yes, this has been considered in the assessment. As mentioned in section 10.6.3, subheading "Buffer and deposition tunnel backfill" the effect is not large in a million year perspective, even if groundwater conditions that would favour erosion were to prevail all the time. This is further elaborated in the advection scenario, see section12.2.2, subheading "Global warming variant and other climate cases", p 580 vol. III. Also, the risk summation is a based on a bounding case where advective conditions are assumed to occur throughout the assessment period in all deposition holes, see section 13.9.

Earthquakes

Q 2.5.22 The frequency of earthquakes is characterized as the largest uncertainty in the assessment of possible canister failure due to shear load. SKB states that seismic events that could impair the integrity would require an induced earthquake of approximately magnitude 5 (Vol. 2 p.297). SKB further admits that further investigation is required in order to determine the extent of damage zone which may host larger earthquakes (Vol. 3 p 834). To mitigate the earthquake hazard, current plans consider the application of the EFPC criterion (Vol. 1 p.157). Is the present knowledge considered sufficient to prove the safety? How likely is such an earthquake at the site?

Indeed, the largest uncertainty regards the frequency/magnitude relation of anticipated earthquakes. The uncertainty grows with the time span of the assessment. Yet the impact is bounded by the use of cautious assumptions (e.g. regarding strain rate) and by systematically using worst cases (e.g. maximum possible earthquake on worst located zone) after having propagated uncertainties in terms of ranges. Yet, further investigations are not only motivated by the need to decrease earthquake hazard, but also to decrease conservatism so that the repository layout might be further optimised. We are confident that long-term safety is adequately demonstrated with the approach of handling the uncertainties taken in SR-Site. The likelihood for large earthquakes at Forsmark is very low. The anticipated frequency is low (Table 10-14, p. 466) and the zones in the immediate vicinity of the repository are not sufficiently large to host large (e.g. M 7-8) earthquakes. The probability of having an earthquake of magnitude 5 or larger at Forsmark, within the nearest 1000 years and within 10 km from the repository, is estimated to be less than one percent (R-06-67, Table 4-3, p. 25).

Number of failed canisters/probability of canister failure

Q 2.5.23 "The containment function is provided by an intact copper shell of the canister" (Vol. 1 p. 42). The analysis indicates that containment is maintained even in the one million year perspective for a vast majority of canisters (Vol. 1 p. 42). SKB states that the number of failed canisters is substantially less than one. That is why the number of failed canisters is interpreted as the probabilities of canister failure (Vol. 2 p.536). What are the consequences if the probability of canister failure is not considered, but the number of canister failure is set to 1 for all cases when a number ≤ 1 has been calculated? How many canisters could fail at maximum, while still maintaining compliance with the risk criterion?

The answer to the hypothetical question depends on which deposition hole the failing canister is assumed to be located in and at what time the failure is assumed to occur. The answer thus depends on subjective assumptions rather than on the distributions of input data for the consequence calculations that have been (pessimistically) derived from the repository evolution in the different scenarios. A case with one canister postulated to fail due to erosion/corrosion is shown in Figure 13-16 and due to shear load in Figure 13-47. As seen in these figures, the margin to the dose corresponding to the risk limit is around an order of magnitude.

One way of answering the question regarding the maximum number of failing canisters would be the following: The mean number of canister failures in the bounding case of the corrosion scenario (correlated hydrogeological model with initial advection in all deposition holes, Figure 13-69) is 0.86 (Figure 12-18). The margin to the risk limit in this case is slightly more than a factor of 10. Thus, around ten canisters may fail in the corrosion scenario while maintaining compliance. A higher number is obtained for the shear load scenario.

2.5.3 Analysis of scenarios

Likelihood of scenarios

Q 2.5.24 The scenarios which have been analysed are classified as less probable and residual scenarios. The residual scenarios are not propagated further in the assessment (Vol. 3 p.573 ff). Namely:

- Buffer advection is considered as a less probable scenario.
- Buffer freezing is considered as a residual scenario.
- Buffer transformation is considered as a residual scenario.
- Canister corrosion is considered as a less probable scenario.
- Canister failure due to isostatic load is considered as a residual scenario.
- Canister failure due to shear load considered as a less probable scenario.

Is this characterisation still valid in case the assumption of the glacial conditions are adapted to the more severe ones e.g. comparable to the Saalian cycle instead the Weichselian? Would the regulatory limits be met if the buffer freezing and/or canister failure due to isostatic load were considered as less probable scenarios?

The characterisation is valid also for more severe climate cases. A main point in the analyses of the scenarios is to consider such climate cases and this is done for both the buffer freezing and isostatic load scenarios. The conclusion that they should be regarded as residual is based on the results of these considerations, see further sections 12.3 and 12.7, respectively.

To answer the second question, one would also need an estimate of the likelihood of canister failures for the two failure modes. Since the result of the assessment is that no route to these failure modes has been identified, no such estimate is available. However, hypothetical cases with both one and all 6000 canisters failing due to an isostatic overpressure, (representing both scenarios, since a freezing buffer could damage the canister through overpressure) is shown in Figure 13-53, section 13.7.1 p 704-705 vol III.

Analysis of scenarios

Q 2.5.25 The two scenarios contributing to risk are the corrosion scenario with assumption of advective conditions in the buffer and the canister failure due to shear load while assuming an intact buffer (Vol. 3 p.618). In all scenarios of canister failure the correct application of EFPC is assumed (e.g. Vol. 3 p.599). SKB states that the number of canisters that may fail depends on the success of detection and avoiding large fractures in deposition holes (Vol. 3 p. 619). What are the consequences if not all existing water bearing fractures will be characterised with the EFPC?

See response to Q 2.5.5.

Buffer advection scenario

Q 2.5.26 SKB calculates that consequences in terms of canister failure are similar (on average 0.17 compared to 0.12 in the reference scenario) if advection is assumed initially in all deposition holes (Vol. 3 p. 574). What assumptions underlie this calculation? What is the reason that the increase is so small?

The assumption is simply that canister corrosion is calculated for advective conditions in all deposition holes from the time of deposition, rather than from the time when advective conditions is calculated to have occurred due to erosion. The reason for the small increase is the longevity of the canister: Even with advective conditions, the overwhelming majority of canisters will maintain their integrity in a million year perspective due to the favourable conditions at the Forsmark site. Put another way, the time required to corrode through a canister is in general much longer than the time required to erode away enough buffer material to create advective conditions.

Canister corrosion scenario

Q 2.5.27 The canister is assumed to fail at 114,000 years after deposition (Vol. 3 p.655). In the most pessimistic variants of the corrosion scenario SKB assumes the first canister failure and hence the first release to occur after around 50,000 years (Vol. 3 p.737).
How is this calculated? Which assumptions have been made? Are they pessimistic? Where is this documented? The failure time has been characterised as the one input variable having the most impact on the dose calculation (Vol. 3 p. 690.) When could the first canister fail at the earliest without jeopardizing the safety?

The canister failure times are calculated using the modelled flow conditions in each individual deposition hole in combination with the distribution of sulphide concentrations in the groundwater.

In the most pessimistic variant of the corrosion scenario, advective conditions are assumed to prevail from the time of deposition; otherwise the corrosion calculation takes into consideration also the time required to reach advective conditions through erosion of the buffer. Also, the most pessimistic variant makes use of the results of the hydrogeological model yielding the highest consequences, i.e. the fully correlated case. The earliest failure time in that variant is obtained when the highest flow rate in a deposition hole is combined with the highest sulphide concentration in the sulphide distribution.

These corrosion calculations are explained in sections 10.4.9 (reference evolution) and 12.3 (corrosion scenario) of the main report with further details provided in the corrosion report, TR-10-66, where references to all data used in the calculations are also found.

It is difficult to establish an earliest failure time without jeopardising safety without specifying also a number of other parameters. The hypothetical pinhole cases in section 13.7.2 are examples of consequences of hypothetical early failures. Here, an initial, penetrating pinhole defect is assumed to grow into a large defect (completely failed canister) in 10,000 years. The examples show that safety is maintained also for such cases.

2.5.4 Additional analysis and supporting arguments

Records and memory keeping to protect from human intrusion

2.5.28 SKB states that countermeasures to prevent inadvertent intrusion are generally assumed to be preserved for between 100 and 500 years. In the assessment SKB assumes that an inadvertent intrusion such as drilling will take place at the earliest 300 years after repository closure (Vol. 3 p.745). Which measures will be implemented to keep and transfer the knowledge about the repository for this period? Where is this documented? How is it assured that the required resources are available?

During the operation of the repository, SKB is obliged to preserve information in accordance with Swedish regulations. During this time information also has to be provided to Swedish government institutions, the European Union and IAEA. Hence, information on the repository will be distributed to many locations. After closure of the repository SKB (and the nuclear utility owners) has fulfilled its obligations according to Swedish law. SKB is after closure (decommissioning) obliged to transfer its archive to the National Archives in Sweden. The responsibility for the repository as well as for maintaining records and knowledge will after closure rest with the Swedish state. In preparation for this transfer of information SKB will, in international cooperation, prepare an action plan for long-term preservation of information on the final repository for radioactive waste. See the license application section 4.10.

SKB is just about to launch a programme in this field which will include various efforts and activities. An essential part of this programme will be to continue to promote and take active part in the current OECD NEA RWMC project concerning Records Knowledge & Memory (RK&M). This strategy is a result of two SKB studies concluded a few years ago about preservation of information about final repositories in Sweden (P-08-76, in Swedish) and preservation of knowledge for the future (P-07-220, in Swedish).

Provisions not to allow an unsealed repository

Q 2.5.29 Based on the analysis of the case of an unsealed repository SKB concludes that the repository *should not* be abandoned prior to complete backfilling and sealing.
What is SKB planning in order to assure that the required financial and personal resources are available at the specific time?

According to The Act on the Financing of Management of Residual Products from Nuclear Activities (SFS 2006:647) the reactor owners are obliged to cover the future costs of spent fuel disposal including closure of the repository, decommissioning of reactors and research in the field of nuclear waste. A fee is levied on nuclear electricity production and deposited in the Nuclear Waste Fund in order to make financial resources available when needed. With funds available it should be possible to maintain the SKB organisation and the personal resources needed. Plans for closure of the repository are presented in the Closure production report (TR-10-17) and decommissioning in an Appendix to the licence application (in Swedish).

Growing pinhole failure

Q 2.5.30 SKB postulates that one canister has an initial penetrating pinhole defect (Vol. 3 p.705). What are the reasons of postulating that there will be only one canister with such a defect? Can the quality of manufacturing and testing methods be assured?

The growing pinhole failure mode is a hypothetical, residual scenario, used to illustrate barrier functions. (Hypothetically assuming a penetrating pinhole defect, several randomly located canisters in the repository would generate hypothetical doses that to a good approximation

would scale linearly with the number of assumed defective canisters.) How the quality of the manufacturing, welding and testing will be assured is described in "Design, production and initial state of the canister" (SKB TR-10-14), and summarised in section 5.4 in Vol I of the main report. As given in e.g. Table 5-9 (page 172) the fraction of canisters with a defect larger than 20 mm (the combination of 2 types of defects) is negligible. A penetrating pinhole defect is therefore regarded as hypothetical.

Time beyond 1 million years

Q 2.5.31 Risk and dose calculations show that the peak is in some cases not reached within 1 million years. Has SKB calculated when the risk and dose peak is expected? What variables have impact on the time of the peak?

The time of the peak dose has not been formally calculated, mostly due to the large uncertainties associated with times beyond one million years. However, the following can be said: The risk is dominated by the corrosion scenario. Extrapolating the development in this scenario to times beyond one million years would yield more canister failures due to buffer erosion followed by enhanced corrosion and, possibly for very long times, also due to corrosion when the buffer is present. The time of the peak would then depend on the distributions of groundwater flow and groundwater sulphide concentration. While additional failures may occur even tens of millions of years into the future, the inventory of the dominant radionuclide, Ra-226, is expected to be unchanged due to the long half-life of its mother nuclide-238. The peak dose may therefore be expected far beyond one million years. In addition, it is noted that a highly hypothetical case where both the canister and the buffer are assumed to be failed initially in all deposition holes yields doses after at million years less than an order of magnitude above the risk limit, see Figure 13-64, section 13.7.3 p. 718. This suggests a (pessimistic) bound on the peak dose value.

2.5.5 Sensitivity analysis

Q 2.5.32 The input variables having the most impact on the total dose at 1 million years are (Vol. 3 p.690):

- the fuel dissolution rate D_{Fuel},
- the transport resistance F and
- the failure time $t_{failure}$

How has SKB handled this in the assessment?

It is not clear what this question means. The variables are identified in a sensitivity analysis at a late stage of the assessment and their identification led to no special "handling". However, these variables (in the case of failure time the underlying variables flow rate at repository depth and sulphide concentration) have been identified as important also in earlier assessments, most notably in the SR-Can assessment, and as a result they were identified as important already in the early stages of data qualification of SR-Site, see further chapter 9 of the SR-Site main report, in particular section 9.3. Also, the outcome of the sensitivity analyses are used when providing feedback to future work, see e.g. Table 13-13.

2.5.6 Robustness

Q 2.5.33 The statements on the robustness (Vol. 3 p.813) are very limited. Does SKB consider them as sufficient? Is it planned to add more considerations to this issue?

The statements on robustness are summaries of statements made earlier in the conclusions chapter 15 and conclusions drawn elsewhere in the main report. The discussion of the safety concept in section 15.3.2 largely consists of robustness arguments and it seemed unnecessarily repetitious to bring them up a second time. Also the results of the comprehensive assessment of residual scenarios reported in section 13.7 are not repeated but the results are referred to as one of the main arguments for robustness. In addition, the confidence argument made up front in Chapter 15 "*The reliance of the KBS-3 repository on i) a geological environment that has long-term stability with respect to properties of importance for long-term safety, i.e. mechanical stability, low groundwater flow rates and the absence of high concentrations of detrimental components in the groundwater, and ii) the choice of naturally occurring materials (copper and bentonite clay) for the engineered barriers that are sufficiently durable in the repository environment to provide the barrier longevity required for safety.*" could be seen as a robustness argument.

We thus consider that due consideration has been given to the issue of robustness in SR-Site whereas the best format for presenting a large set of conclusions from a complex analysis may always be discussed.

2.5.7 BAT

Q 2.5.34 In Section 14.3. SKB discusses several techniques to demonstrate optimisation and the use of BAT (Vol. 3. p. 761 ff). How has SKB decided which techniques are assessed to demonstrate optimisation and the use of BAT? Which criteria and which procedures have been applied in the selection? Where is this documented? Which alternative techniques have been assessed but not been chosen and why? Where is this documented?

As a general rule, decisions for selecting a certain technique are primarily based on safety and feasibility, i.e. only techniques that can realistically be achieved and that provide sufficient safety can come into consideration. If there is more than one technically feasible option the technique offering most safety would be selected, where safety is considered both in terms of potential impact on risk and what is judged to be the more robust option. If differences in safety are judged marginal, the technique judged to be more feasible and economical is selected.

The more general aspects of BAT and how SKB has reasoned the selected method is described in Section 5 of the "*Application for licence under the Nuclear Activities Act for construction, ownership and operation of a nuclear facility for the final disposal of spent nuclear fuel and nuclear waste*". A more detailed account is provided in R-10-25 "*Choice of method – evaluation of strategies and systems to manage spent nuclear fuel (MV)*"; in Swedish with a summary in English.

As stated in the SR-Site Main report p. 761 ff, the BAT discussion in SR-Site is limited to "*the KBS-3 method with vertical deposition, using copper/ cast iron canisters, buffer and backfill at the selected site.*"

Technical design decisions regarding the reference design in the licence application, including an assessment of alternatives, are all formally justified and internally documented at SKB in accordance with SKB's management system.

Q 2.5.35 SKB recognizes that when applying an inflow criterion instead of the EFPC all unsuitable positions will be identified (Vol. 3 p.765). Why is the more strict inflow criterion not applied? Does SKB plan to apply the inflow criterion at a later stage?

We do not claim that an inflow criterion would definitely identify all unsuitable positions, but that the results suggest (as expected) a strong correlation between high inflows under open conditions and high flow rates after closure and saturation. A combination of EFPC and inflow criteria appears to be a very good means to enhance safety. This is also why SR-Site suggests that the Design Premises should be updated to also consider inflow criteria (see page p. 828). Such an update is now actually being considered in the ongoing work for revising the design premises.

The reason why such a criterion was not considered prior to SR-Site is that it was then not fully clear how useful it would be and how it could be applied in a defensible way in the hydrogeological modelling in the safety assessment. However, given the results from SR-Site it is clear that work on defining suitable inflow criteria should be further pursued.

2.5.8 Public Participation

Q 2.5.36 According to international recommendations, e.g., IAEA or NEA, stakeholders and the public ought to be included in the process of realizing a final disposal. What public participation measures have been used during site selecting and with regard to SKB`s application for construction? Which public participation measures will be implemented in future? Where are they documented?

SKB has conducted extensive consultations with stakeholders and the public in accordance with Chap. 6 of the Environmental Code. More than 60 consultation meetings have been held mainly in the municipalities of Östhammar and Oskarshamn during the period 2002-2010. The views expressed in the consultations have been considered in the preparation of the applications with appendices. Further information on the consultations and the responses given by SKB to issues raised is provided in the EIS, in the consultation report included as an appendix to the EIS and on the SKB website (under "Consultation and dialogue"). SKB plans to continue the dialogue with the municipalities concerned, other stakeholders and public also in the future.

2.6 Questions from IRT Member 6

These questions are based on a partial review of TR-11-01 and some background reports.

Q 2.6.1 Has SKB prepared a concise (20-30 page), plain language synopsis of the factors that contribute to the long-term safety of the repository? By this is meant a simple, easy to understand summary for the non-technical person of how the materials to be disposed, the site, and the repository design work together to provide for the overall safety of the repository. If such text only exists in Swedish, would it be possible to have it translated?

SKB has identified the need for a concise plain language presentation of the factors that contribute to long-term safety. To meet this need SKB has initiated a project to produce a short movie describing repository development after closure and the factors that contribute to safety. It will be produced in Swedish and English. However, it is not likely to be completed within the project time of the IRT.

Q 2.6.2 Please describe the measures that SKB will take during construction and operation to monitor key geotechnical and design parameters in order to identify deviations observed from those conditions assumed in the license application that may affect compliance with applicable safety regulations. In particular, how will SKB use data collected during this period to verify its modeling assumptions?

As stated in section 5.8.4 a "*control program will be developed prior to excavation, with the objective of ensuring that the design premises and other requirements on the construction work and on the operations are fulfilled. The control programme will consider material deliveries, workmanship and control of the as built and operated facility relative to the design and specification of operational activities*". Examples of such controls are discussed in section 6.4 of the Underground Openings Construction Report (SKB TR-10-18). However, the objectives and contents of the control programme will be defined in much more detail prior to the underground construction work, and will evolve and be adjusted in response to experience gained.

Generally, the controls and the monitoring aims to establish the feasibility of a constructed deposition tunnel and potential deposition holes prior to canister emplacement in the deposition tunnel. If the analysis shows that conditions conform to the Design Premises deposition could then go ahead, and if not – the deposition tunnel will be rejected on not used for deposition.

In addition, as described in "*Verksamhet, ledning och styrning – Uppförande*", (in Swedish, Activities, management and control) all monitoring and characterisation data will be assessed and interpreted into an updated Site Descriptive model. This in turn will be input to an assessment of the safety implications and will be documented in an update of the Safety Report (SAR). In case deviations would imply reduced safety, this will be reported to SSM and actions will then be taken/suggested e.g. by design modification or ultimately by retrieving canisters from affected parts of the repository. Such updates of the Safety Report will be made in case there are major deviations between expected and found site characteristics and also at some regular intervals.

2.7 Questions from IRT Member 7

These questions from IRT member are based on a once-through reading of SKB TR-11-01, the main report of the SR-Site Project, Volumes I, II and III.

Policy and other provisions to keep memory of the repository and also to avoid an unsealed repository

Q 2.7.1 The length of time it will take to build, fill and close a repository is of concern with respect to political, social and economical stability in a country. There is no example in the world of a similar large project that has needed this type of intense management and institutional control over such a long time, and certainly not for something as potentially harmful as spent fuel. SR-Site analyzes a completely filled repository with all deposition tunnels sealed but with the central area and the main shaft left open. What about a partially filled repository in which several deposition tunnels are left unsealed? The argument (made in SR-Site with respect to nuclear bombs) that, if this were to happen as a result of political, societal or economical problems, these problems would probably be more catastrophic than a left-open repository may be weak. Perhaps more attention needs to be paid to this possibility and how, in a changing situation, an unfinished repository can be made always passively safe; for instance, should there be criteria as to how fast finished tunnels should be backfilled and sealed?

The case of an incompletely sealed repository is discussed in section 14.2.8 in the SR-Site Main Report. Each deposition tunnel is backfilled and sealed as soon as the canisters have been emplaced in the tunnel. Hence, no deposition tunnel will be left open for any length of time. The time required for deposition and backfilling of a single deposition tunnel is approximately 4-6 months. When a deposition tunnel has been sealed the main barriers are in place and the spent fuel is passively safe. The consequence of leaving main tunnels, shafts and ramp without backfill are described in section 14.2.8 in the SR-Site Main Report.

Q 2.7.2 At some older nuclear sites in the world that are undergoing clean-up or decommissioning, there are considerable problems with existing records, and understanding of those records, kept over a time span of at most 50 years. The time span over which records must be kept for a repository while it is being excavated, filled and closed may potentially be much longer. How has SKB considered this?

See response to Q 2.5.28. Is should also be noted that today the requirements on documentation of nuclear facilities is comprehensive compared to what they were 50 years ago.

Effects of water freezing

Q 2.7.3 Potential freezing of the repository is limited to freezing of free water. Permafrost penetration to repository level and buffer and backfill freezing occurs at lower temperatures, -2°C and -4°C. These isotherms do not reach the repository in the analysis. However, they come quite close in some cases in the analysis (i.e., with not a lot of margin, Figures 12-7, 12-8, 12-10, 12-11). While these cases may not be realistic, there could be many benefits to moving deeper with the repository such as even less fractured rock, less likely to have to reject deposition holes, longer timeframes for intrusion of dilute water, etc. There are also arguments against going deeper, mainly rock stress and perhaps costs? A better weighing of arguments pro and against going deeper could be made. As the case reads now, one gets the impression that much can be gained from locating the repository deeper but that the idea is rejected on weaker arguments.

A comprehensive discussion of the motivation of repository depth is given in section 14.3.4, including the risk of freezing. The discussion in section 14.3.4 p. 769ff aims to show that there is little benefit in going deeper. However, for clarity the following arguments against going deeper than the current 470 m could be stressed:

- **On p. 770 it is stated that "*placing the repository at 400 m or 500 m depth does not significantly increase the risk for excavation-induced spalling*". However, given the relatively high stress levels and the uncertainty in stress may imply an unnecessary high risk for stress related construction problems if going even deeper (i.e. below 500 m).**
- **There is an economical argument against going deeper since this would imply an increased footprint (and more tunnels) due to the higher initial temperature. In addition, access ramp and shafts would be longer.**
-

Q 2.7.4 The argument on P. 592 why even the possibility of water freezing (0°C isotherm) is very unlikely seems somewhat weak. It is always somewhat risky to analyse the most pessimistic conditions, finding some effects and then trying to argue that those effects are not serious or would not occur because the case or conditions are deemed unrealistic. With the occurrence of the Fukushima disaster, this type of arguing may be more vulnerable now. There should be more emphasis on the -2°C and -4°C isotherms not reaching the repository depth, it is these isotherms that affect safety functions. And it these safety functions that could perhaps benefit from more margin by going deeper with the repository.

See response to Q 2.7.3.

General

Q 2.7.5 With respect to the feedback to assessed reference design and related design premises, SKB has presented its case and found no deficiencies. By mentioning reasons to revise the reference design one admits that no design will ever be perfect. At what point is it safe enough? It is safe now, according to SKB, in 2011 with the publishing of SR-Site. So there have to be compelling reasons to further refine the design in the future. Are there guidelines as to which improvements should be accepted, which rejected, what would guide this (the law of diminishing returns)?

The level of safety of the KBS-3 repository at Forsmark assessed in SR-Site is indeed judged sufficient. The main reason for further technical development and design change concerns the challenges involved in detailed design and implementation of the various components and procedures of the KBS-3 system. To ensure that this detailed design and implementation stage will work efficiently, it may also be necessary to revisit some of the design premises. For example, the current FPC/EFPC is shown to provide sufficient protection against the earthquake hazard, but we also know that its implementation would imply that most deposition holes rejected by this criterion would not be vulnerable to earthquakes. A more efficient criterion, but resulting in at least the same level of safety would thus by very useful.

In addition, while the current design is shown to result in a safe repository, it is in keeping with a good safety culture to assess how/whether the system could be improved for even more safety, especially if the modifications made would not imply undue additional costs.

Boreholes management

Q 2.7.6 What is done with rejected deposition holes? It is not explicitly stated in SR-Site that they will be filled in. If deposition holes that were rejected because of too-high water inflow were left open they could fill with water, in which development of microbial activity could occur, producing organic matter that may not be desirable for a repository. Can it be stated that any rejected cavity will be grouted and filled in order not to have anything filled with water left in a repository? On P. 193, in Figure 5-17 it appears that rejected boreholes are filled in with backfill. This seems not mentioned anywhere else in SR-Site. Why is backfill used and not buffer? Backfill may allow microbial activity.

It is confirmed that the plan is to fill rejected deposition holes with backfill. No canisters are emplaced in rejected deposition holes. Hence, they can be considered as a part of the deposition tunnels, with the same requirements (or even lower).

Q 2.7.7 There seems to be some doubt or ambiguity about the bottom plate in the SR-Site report. Is there not a simpler way of evening out the bottom of a deposition hole than the added complication of a bottom plate? Could SKB devise a method by which to compact a bottom layer of bentonite with a flat top *in situ* on which the first bentonite block can be placed? The inclusion of bottom plates seems to unnecessarily complicate the safety case of the design.

True, one conclusion from SR-Site is that the current design of the bottom plate is far from optimal. An improved solution will be needed and development work seeking a solution without a bottom plate is underway.

Q 2.7.8 Could modelling and direct observation be accurate enough to predict most the locations of holes that would be rejected because of the presence of water-bearing fractures, such that they are not even drilled? If too many boreholes are in need of rejection this could affect the foot print of the repository.

This is clearly an aim of the underground characterisation programme. Most water-bearing fractures would be detected either as they are mapped in the excavated deposition tunnels or intersected by the short pilot holes drilled prior to the full diameter drilling of the deposition holes. It could also be mentioned that Posiva is testing this in their ongoing demonstration tunnel tests and that SKB aims to make further tests on this at Äspö HRL. Thereby it should be possible to minimize the number of deposition tunnels or deposition tunnels first excavated and then rejected.

Q 2.7.9 Could one grout the fractures intersecting the deposition holes, such that water comes in by diffusion only? Why does some degree of piping have to be accepted? Is the addition of grout too much of a problem for the bentonite buffer?

Even deposition holes with no measureable inflow could be subjected to piping. One example could be a case where the inflow is drained to another location in the tunnel which later seals. Another problem would be to ensure the long-term durability of the grout. Furthermore, deposition holes with inflows to an extent that grouting would be required would likely not be suitable in the long term, since there is a strong correlation between high inflows under open conditions and high flow rates in the long term and since the grout is eventually expected to degrade after saturation. See also Q 2.5.35.

Fuel

Q 2.7.10 Due to high BU fuel (P. 164), canisters will be deposited that will be only partially filled According to Figure 5.7 there will be about 600 of those, which is 10% of all canisters. Has it been considered to use canisters of different dimensions for these fuels rather than part-fill the reference canisters, for instance to save on materials? Is there more room for water than the stated 600 mL in these part-filled canisters or are they backfilled with something? If so, with what? If not, is there a problem with the empty space in these canisters?

It has been decided to develop two types of inserts, BWR and PWR, and that these could encompass all types of fuel. To use one type of copper shell (one set of outer dimensions) simplifies the development and operation of welding, transport, handling equipment etc. Special canister types have not been considered.

The maximum of 600 g water is the limit for how much water that is allowed after drying of the fuel (water left between the zirkaloy tubes and the fuel in case of damaged fuel), and regards an intact canister. This will not change if the canister is only partially filled. The amount of nitrogen gas from air left in the canister will increase (the nitrogen could form nitric acid), but the increase of the void volume would be rather small (e.g. about a factor of 2 for half-filled canisters, see the Data report SKB TR-10-52, section 4.1, and the effect negligible.

For a failed canister with a hole all through the copper the void volume that could be filled with water increases with the same factor of about 2. This would prolong the time required to establish a pathway through a hole in the copper, but the effect is negligible compared to other uncertainties in the process.

Criticality, in particular for a failed canister into which water has intruded, is analysed also for a canister with 10 or 11 fuel elements, in addition to the ordinary filling with 12 elements. The risk for criticality is decreased with a larger void volume (fewer fuel elements) in the canister: a larger amount of water, but less fuel material.

Backfilling of partially filled canisters has not been considered.

Q 2.7.11 In Table 5-4, the calculated inventory, based on type containers, is always somewhat higher than the inventory assumed in safety calculations. This is then argued away taking fuel ages into account. This may create the notion of an argument after the fact. Could some calculations be provided that show that this is not detrimental, rather than just making the argument?

The text in the report is a little misleading. The "reference scenario" refers to reactor operation and not to a safety assessment scenario. It is actually the "total in all type canisters" inventory that is used in the assessment, not the "total for the reference scenario".

Q 2.7.12 The more recent ideas on what may affect fuel stability, i.e., alpha-self irradiation, radiation-enhanced diffusion, He-build-up and the influence from high BU are not discussed in SR-Site but the reader is referred to the fuel canister process report. A more thorough assessment of these effects in the main document would seem warranted. In some countries (especially France) some of these potential effects have been given much attention. What do the Swedish fuel specialists think of these potential effects? For example, what about fracturing of the fuel and increasing the fuel surface and dissolution rate as a result of He production?

It is true that fuel stability is discussed only shortly in the main report, while the issues raised by the reviewer are discussed in detail in the Fuel and Canister Process Report (TR-10-46, sections 2.4.2, 2.5.5 and 2.5.8). ASIED (Alpha Self Irradiation Enhanced Diffusion) was considered to contribute substantially to radionuclide redistribution in the fuel in publications from the French program until about 2006. However, more recent modelling and experimental data from the same program (discussed in section 2.4.2 of TR-10-46) showed that diffusion coefficients were orders of magnitude lower. The same holds for the helium issue in UO_2 fuel, discussed in detail in section 2.5.8 of TR-10-46. The influence of high burn-up on fuel dissolution is discussed in section 2.5.5 of TR-10-46.

Canister/Corrosion

Q 2.7.13 How was the corrosion depth value of trapped atmospheric O_2 (< 500 µm) derived (P. 316)? Calculated values given in the preceding text were 17, 34, 106, 260 and 768µ, depending on assumptions. How is < 500 µ derived from this? Would it not be better to say that the depth would be < 768 µm?

It is deemed too pessimistic to assume that all oxygen in the tunnel reaches the canister. With the considerations of diffusion times compared to when all oxygen is consumed also by other processes the 260 µm on the top part of the canister is more realistic. Added to this is the corrosion from the buffer , maximum 34 µm, and the surface roughness of maximum 50 µm, which sums up to about 350 µm. This was rounded to an upper value of 500 µm.

Q 2.7.14 What does it mean that 10^{-6}canisters may be sheared (P. 430)? What does it mean that less than 8.3 x 10^{-3} canisters may fail (P. 480)? If it means that < 1 in all of the 6,000 canisters may fail, why not just say that?

The cited statements mean that these are the mean number of failed canisters as results of probabilistic calculations. The reason for specifying the numbers rather than saying <1 is that the ultimate calculation end-point is a risk, meaning that it is essential to quantitatively establish the probability of failure as well as the consequences associated with the failures.

Q 2.7.15 Does the argument of evening out corrosion really work (P. 430)? What if the bottom of the defect was affected by the same rate of corrosion as the non-defected surface area of the canister? Would it never even out then? What would be the consequences in that case?

It is not fully clear what the question is referring to. To get a defect to corrode only at the bottom and not the sides of the defect or cavity requires a process that infers a different environment at the bottom, and the thorough review of corrosion processes in the state-of-the-art report on corrosion (SKB TR-10-67) has not revealed any such process. If the corrosion proceeds in such a way there will be no evening out and the corrosion distance to penetrate the

copper at such a spot would be less than the average distance. For internal defects, no evening out can be accounted for, which is mentioned on p. 598 and discussed in the corrosion calculation report (SKB TR-10-66, section 4.3.4). Processes for localised corrosion is discussed in the state-of-the-art report (SKB TR-10-67, section 5.3) where it is concluded that copper in repository environment will not undergo classical pitting corrosion, but rather a form a surface roughening.

Q 2.7.16 There are some inaccuracies with the notation of safety functions (P. 746, P. 755). Can 1 says "provide corrosion barrier", not "ensure containment" in Fig. 10-2, and Bf1 is BF1 in Figure 10.2. They should be word-for-word the same to prevent confusion.

Agreed. These issues are noted as errors and will be corrected. The notations in Figure 10.2 are the correct ones.

Q 2.7.17 Information about pitting corrosion and SCC appears scarce or absent in SR-Site. Were they shown to not be important? What are the arguments for leaving these processes out of SR-Site?

It is correct, the information on pitting (or local corrosion in more general terms) and stress corrosion cracking is scarce in the main report of SR-Site. Local corrosion is thoroughly discussed in the updated state-of-the-art report on corrosion (SKB TR-10-67). Stress corrosion cracking is likewise described in TR-10-67 and also in a report dedicated to SCC mechanisms (SKB TR-10-04). The Fuel and Canister Process report (SKB TR-10-46, sections 3.5.4 and 3.5.5 respectively) motivates the handling in SR-Site. Localised corrosion when the environment is still oxidative is found to be a surface roughening rather than classical pitting and is handled by adding a corrosion depth of ±50 µm to the average corrosion depth caused by the initially trapped oxygen. Stress corrosion cracking during the initial warm aerobic phase is found to be highly unlikely as several conditions need to be fulfilled at the same time (potential above the Cu_2O/CuO equilibrium line, an SCC agent present as well as tensile stresses). High temperature and chloride tends to suppress cracking. As for the anaerobic phase cracking has been shown in sulphide solution, but only in bulk concentrations much higher than expected in the repository environment where the sulphide transport is limited by the bentonite (SKB TR-10-67). There is neither any mechanism found to support SCC during anaerobic conditions (SKB TR-10-04).

The processes are thus not left out of SR-Site, but treated according to the methodology, which in these cases means that they are argued in the Process report to be unimportant and thus only briefly discussed in the main report.

Buffer/Backfill

Q 2.7.18 In SR-Site both the terms dry density and saturated density are used which is sometimes confusing. It would be easy to provide a graph showing the relationship between dry density and saturated density, such that, if both terms are used, the reader can convert one value into the other easily.

The saturated density can be seen as a confusing and unnecessary term. However, it has a strong tradition in the Swedish program and it is difficult to get rid of it.

Q 2.7.19 The original water content in the buffer material is adjusted to facilitate the manufacturing process (P. 185). What type of water is used for this? "Dry" bentonite may contain 7-9% water, so the water added could be 8 – 10% to arrive at a water content of 17%. There is a danger of adding unwanted elements (such as organics, sulphides and sulphate) if no controls are put on the quality of this added water.

Most likely the bentonite will be purchased with a water content at 17%, or very close below. Drying of bentonite is an expensive process, while transportation of a little extra water is cheap. This means that the addition of water will be limited and ordinary tap water can be used.

Q 2.7.20 In Table 5-17 (and on P. 190 – 191) there are a number of dry densities specified for pellets, loose filling, etc. What is the rationale of all these different dry density values, aperture restrictions?

The densities of blocks and pellets in the backfill are those that can be readily achieved from a manufacturing and installation (pellets) point of view.

Q 2.7.21 The process of metallic iron affecting the montmorillonite in bentonite has been considered although the actual process is not really discussed in SR-Site. However, another potential process, i.e., buffer cementation due to iron corrosion products (from the inserts, once containers have failed) appears to be missing. Is the reason for omission of this potential process that containers fail only when the buffer is eroded, and not by any other means, such that it would not matter what Fe corrosion products would do to the buffer? It would still be advantageous to consider what could happen to some of the buffer functions if buffer were cemented by iron corrosion products. Has this been considered?

This could possibly have been presented in a clearer way. Since the corrosion products originate from the metallic iron, they are included in the general term "iron-bentonite interaction". Cementation is discussed in general terms in the report, more focussing on the consequences than the cause. Cementation is of primary importance for mechanical interactions between that canister and the buffer and is therefore of less concern after canister failure even if the buffer would be present.

Q 2.7.22 Radionuclide transport is considered to be diffusion controlled in the buffer because of its tight contact with rock (P. 255 and P. 260). In laboratory experiments, it has been shown that microbes can move along the interface between a bentonite plug and the walls of a pressure cell, but not through the bentonite matrix, Therefore, rock-bentonite interfaces could possibly be preferred transport routes, because of the clay gel layer at the interface between bentonite and rock. Is this a credible process, has it been considered? Or is it disregarded because radionuclides can only escape from failed container and containers fail only when the buffer fails (i.e., erodes)? Should such a process not be analyzed anyway?

The key problem with microbes is their potential ability to reduce sulphate to sulphide. This would be a problem if it could occur inside the buffer or at the buffer/canister interface, since the copper corrosion then could be controlled by the mass transfer of sulphate. Microbial activity in the buffer/rock interface on the other hand would have similar consequences as microbial activity in the rock.

Q 2.7.23 Rather than sinking, could the weight of the canister just compress the bentonite? Could that lead to less dense buffer elsewhere in the deposition hole by initially creating a space near the top of the canister (P. 255)?

It is basically the friction between the bentonite and the canister wall that keeps the canister in position. If the friction was neglected, compression could occur, but the effect would be very small since the swelling pressure increases sharply with the density of the bentonite.

Q 2.7.24 Gas transport through compacted buffer appears to be not well-characterized or known (P. 265), even after reading section 13.8. Is more work planned on this?

Yes, SKB is operating a full scale gas migration experiment at the Äspö Laboratory. This experiment is currently a part of the EC gas project FORGE.

Q 2.7.25 On P. 256 it is stated that repeated freezing and thawing has no effect on the sealing properties of buffer while on P. 265 it says that repeated freezing may affect the transport properties of backfill. This seems to be a contradiction; both materials are bentonite-based.

The statement about the backfill is cautious. The lower montmorillonite content in the backfill could potentially lead to a redistribution of the accessory minerals during freezing/thawing cycles, which potentially could change the transport properties.

Q 2.7.26 In the reference evolution of the buffer an important process appears to be missing (e.g., P. 368-371, P. 389 and P. 395. 397). The initial drying out of the buffer because of high temperature from the fuel in the canisters is not discussed explicitly. Only a drying out of the buffer because of dry rock during installation appears to be considered. Buffer will initially dry out and may crack as a result of the high canister temperatures. These cracks could be quite long-lived depending how fast the water saturates the buffer which has quite a time span in the analysis. When these cracks "age" they may become encrusted and "cemented" by salt deposits and perhaps by other minerals. Is it certain that they heal again fully to their original density and to full swelling pressure, when the buffer saturates? If complete sealing of these cracks did not occur, what could be the consequences?

The high temperature from canister will only cause redistribution of water within the buffer, not a net drying, under repository conditions. This is the reason why only the dry rock is treated as a separate case. The redistribution of water is included in the assessment and is mentioned on P. 370, admittedly, this may not be very obvious. It is true that the bentonite may fracture during this period. There may also be some redistribution of minerals already present in the buffer. However, the system can be considered as closed with respect to vapour so severe precipitation of salts cannot occur. Experimental and natural observations, see e.g. TR-09-29 section 7.2, show that the bentonite will recover its properties when it is saturated.

Q 2.7.27 In the analysis on P. 384 – 386 the possibility of very low swelling pressures is shown both in buffer and backfill. But no comment is made with respect to loss of safety functions of buffer and backfill in these pages, including the loss of enough density to keep microbial activity to a minimum. Has the possibility of increased local microbial activity and its consequences been analyzed?

This section only covers the mechanical aspects. The mass losses leading to loss of safety functions are propagated to section 10.3.11 where the route to advective conditions in the buffer is discussed.

Q 2.7.28 The idea of lowering the dry density of buffer to improve the shear failure analyses (P. 808) causes some concern. High density is needed for other safety functions such as suppression of microbial activity. This idea seems to leave the door open to reducing swelling pressure through decreasing dry density but it is not propagated to the other safety functions of the buffer. Even if the reduction is such that other safety functions are still okay, there would be a loss in the margin of safety for those functions. All other safety functions would need re-evaluation if a decision to reduce buffer dry density is made. For example, has SKB shown the margin in dry density for microbial activity? Buff 2 just stipulates high dry density, what is high, are there numerical values?

The meaning of the expression on page 808 is that the maximum density in the interval should be lowered while the minimum should be retained. This could be achieved by an improved understanding of the production and installation. The swelling pressure increases with ~7 MPa between 2,000 and 2,050 kg/m^3 saturated density, which means that a small reduction of the maximum value will have a large impact on the stress.

Recent experimental work has indicated that there may not be a clear cut-off value for microbial activity with respect to swelling pressure/density. This is discussed further in the Buffer, backfill and closure process report, TR-10-47 section 3.5.15.

(Geo)Chemistry

Q 2.7.29 P. 240 mentions chemical reactions between bentonite and concrete. What are they? Are they treated? How, where?

Initial dissolution of CSH-phases in the tunnel plugs will cause a pH-plume in the backfill. This is described in Section 10.3.12, page 413 - 415.

Q 2.7.30 The calculations on P. 348 cause some confusion. Why was the calculation done for dilute salt concentrations of 1 g/L which is well above the dilute criterion of 0.3 g/L for erosion of buffer? If only 1-2% of boreholes drop to 1g/L, is there still a problem (1g/L is still much higher than 0.3 g/L)? A similar calculation is done for 3 g and 0.3 g on P.501. The different values are confusing, as well as the use of both mmol and g/L when considering dilute conditions. This could be standardized.

We agree that a standardization concerning units would have been preferable. The concentrations on P. 501 are the relevant ones to use; i.e., the initial concentration is 3 g/L, and it is assessed how many deposition holes that will experience conditions more dilute than the threshold value of 0.3 g/L. The chosen values on P. 348 are more questionable; it would have been more appropriate to assess a dilution to 3% of the original value of 10 g/l (i.e., how many deposition holes would experience conditions below a concentration of the threshold value 0.3 g/L). However, the presented case is still pessimistic.

Q 2.7.31 How much will salts present in buffer and backfill materials affect groundwater salinity at repository depth? Has this been studied or modelled in other documents? If so, it could be mentioned in SR-Site and the reader referred to the pertinent document. Does dilute glacial water really stay dilute or will it pick up salts from fracture fillings in the rock and from buffer and backfill salts? Are there any data, or ongoing or planned studies?

There are several characterisations of bentonite, see TR-10-60. It is not possible to know at present what will be the exact composition of the bentonite in the projected repository. Different bentonites might eventually be used in different parts of the repository, considering the relatively long operation period. In any case, the leakage of salts, except for the minor dissolution of calcite, has not been modelled in SR-Site, which is judged to be a pessimistic approach. Taking into account the long time periods involved and the large amounts of groundwater flowing by the deposition holes, the effect on the groundwater salinity is not expected to be large. Furthermore, this would *not* affect the salinity of the groundwaters *reaching* the deposition holes, it would, rather, affect the salinity of the groundwaters *leaving* the deposition holes. The effect on the groundwater of gypsum originally present in the bentonite has been assessed in one of the supporting documents to SR-Site, TR-09-35. It is likely the calcium from gypsum dissolution would prevent bentonite erosion. However, the gypsum content is not sufficient to last for the entire assessment period. Especially not in deposition holes exposed to relatively high water flow.

Glacial melt water will in general not stay diluted. This is discussed, for example, in sections 10.3.6 and 10.4.6, subsections "penetration of dilute water", page 347, Fig.10-32, and page 501, Figs. 10-139 and 10-140. The conclusion is that only a limited fraction of recharge paths are so fast that out diffusion of more saline water from the matrix will not restore the salinity to a level where montmorillonite colloids are stable. See also the discussion on page 292, section 10.1.3.

In the answer to Q 2.4.11 it is concluded that the numerical simulations show that infiltrating glacial melt waters are expected to gain salts through mixing and matrix diffusion, resulting in salinities at repository depth being essentially equal at the beginning and end of a glacial advance/retreat period. In addition it is concluded that there is no evidence of recent waters of glacial origin at repository depths within the repository footprint (it is to be noted that the hydrogeochemical model includes in the repository groundwaters a meteoric-glacial component older than the last glaciation, see report R-08-47, sections 1.3, 2.5, 7.3.3). However, because absence of evidence is not evidence of absence, and because the numerical simulations have several limitations, such as a coarse discretisation, the analytical calculations referred to in question 2.7.30 were performed in an attempt to shed additional light on the penetration of dilute water, and to address model uncertainties.

Q 2.7.32 Global warming may cause an increased inflow of carbonic acid and sulphate (P. 547 and 548). If subsequently SRB turn this sulphate into sulphide, sulphide concentrations could increase. However, it is also stated that sulphide levels are expected to remain the same as current groundwater concentrations at Forsmark. If this is expected, then any increase in sulphide has to be counteracted, for instance by precipitation with Fe. Is there sufficient Fe to counteract any potential increases in sulphide levels in case of global warming?

It is judged that the Fe(II) contents of the rock matrix and the fracture minerals will counteract any increased production of sulphide due to increased infiltration of sulphate. This is not explicitly mentioned in SR-Site's main report. A statistical analysis of the fracture minerals at Forsmark is reported in R-09-30, and the reducing capacity, including Fe(II) contents, is reviewed in report TR-10-57. The Fe(II) contents of the rock matrix is around 1.5 weight %, see section 5.4.1 in TR-10-57.

It is nevertheless believed that the highest impact, in terms of sulphate infiltration, will be during periods where the site will be submerged by marine waters, as it was during the last Littorina period. Higher sulphate concentrations is some rock volumes at Forsmark are due to the Littorina influence, see for example Fig. 6-8 in TR-10-54, showing sulphate concentrations versus depth and Fig. 4-14 in R-08-47 showing Littorina proportions versus depth. The present day conditions reflect the recent influence of marine waters and relatively high sulphate concentrations. Therefore, the conclusion is made that present day sulphide concentrations reflect periods of relatively high sulphate infiltration.

Q 2.7.33 Is there an inconsistency on P. 710 and 711? It is stated that sorption of Ra-226 in tunnels and soil reduces transport and dose considerably but on P. 711 it is stated that Ra has no affinity for bentonite. Buffer and backfill are both bentonite-based. So what is Ra sorbing on in the tunnels?

On p. 710, the effect of sorption in soils and tunnels is investigated. This is done by turning on/off sorption in segments of the flow paths that pass through CPM regions of the model. The CPM regions include both soils and tunnels; we did not distinguish between the two types of media in the performed analysis. Subsequent calculations that look at effects of soils and tunnels separately show that Ra-226 is retarded in near-surface soils but not in the tunnels. This is thus consistent with the statement on P. 711 that Ra does not have a strong affinity for bentonite. Sorption of Ra-226 in soils is not to bentonite, but rather to e.g. organic material.

Q 2.7.34 The conclusion that no gas hydrates will occur at repository depth as based on permafrost studies seems to contradict the studies quoted. These studies indicated gas hydrate formation or past presence (P. 791). What would the effects be of the presence of gas hydrates on a repository? Why are they a concern?

In this section of the main report, we discuss how studies of natural systems have provided information and knowledge which are of use for the SR-Site analysis. For a more detailed discussion about this process we refer to the Geosphere process report (TR-10-48 p. 212). As mentioned in the process report, the process is analysed in a modelling study reported by Bahman et al. (2010), where it is concluded that there is no potential for methane hydrate formation at Forsmark.

Microbiology

Q 2.7.35 Has microbial activity as a result of superplasticizers (SP) in concrete materials been considered? On P 367 it is stated that the contribution of SP to the C concentration will be negligible. On what is this based, where can calculations be found? SP is largely C and for 1-2wt% in grout, this could contribute a considerable amount of C, depending on the amount of grout and concrete used.

This is not explicitly discussed in SR-Site's main report. The influence of superplasticizers, and of all other organic matter added in the repository is discussed in TR-10-19. Many conclusions in section 10.2.5 in SR-Site's main report are based on the supporting report.

Q 2.7.36 Nitrate-containing water is pumped out (P. 311). Many microbes are very capable of nitrate reduction (switch to nitrate as electron acceptor after O_2 concentration has been exhausted by aerobic respiration) and this may be the main reason why the fracture waters appear unaffected by any nitrate.

(This is a comment rather than a question.) True. SKB has the intention to collect more data on the immediate influence of tunnel excavation on groundwater chemistry. All data suggest that if there is an influence, it lasts only a few days.

Q 2.7.37 High sulphide concentrations are identified as a concern in SR-Site, and sulphate reduction may have been enhanced in some boreholes by grunge in the boreholes (P. 360). Was there any material placed in the boreholes that could have leached organics? See for instant a recent paper from the Mont Terri project in which sulphate reduction completely dominated the geochemistry of the water in a borehole. The organics came from pH electrodes that leaked glycerol. This illustrates how something unexpected or overlooked can have considerably consequences for microbial and geochemical reactions.

The answer to Q 2.5.13 is suitable here as well. There is evidence now of processes happening within the sampling equipment: leakage of organics and or corrosion of metals, and a complex series of microbial processes resulting in high sulphide concentrations while water is stagnant in the equipment. The results are perhaps comparable to those of Mont Terri, an evaluation will be started as soon as possible.

Q 2.7.38 Microbes will use up O_2 largely in the backfill but not in highly compacted bentonite (P. 365); that distinction should be made, if one of the safety functions of the buffer (Buff 2) is to reduce microbial activity in thee buffer.

(This is a comment rather than a question.) No credit is taken for microbial consumption of oxygen in the buffer.

Q 2.7.39 On P. 596, a swelling pressure of 1 MPa is used as a criterion below which microbial activity may be enhanced. However, in Figure 10-2, the Buff 2 criterion for reducing microbial activity is high density. Density and swelling pressure are related and perhaps the safety function for reducing microbial activity should be both high density (with a numerical value) and a swelling pressure of > 2MPa? Which factor actually controls microbial activity is not entirely clear.. Density may affect the pore space available for microbes while swelling pressure may inflict a pressure higher than turgor pressure on microbes. Either effect would limit microbial activity. What is SKB's opinion on these two effects, are they not distinguishable or is one of these dominant in reducing microbial activity?

The text on p. 596 is incorrect. The 1 MPa criterion should refer to advective conditions, not microbial activity. However, it is still true that microbial activity could be enhanced if there was a severe transformation of the montmorillonite mineral. In this particular case, the swelling pressure would decrease while the density would remain practically unchanged. A density criterion is therefore not appropriate, since it would work only for a given mineral composition.

2.8 Questions from IRT Member 8

These questions are based on the lectures given by SKB and on the SKB TR-11-01 document.

2.8.1 Initial State

Canister Design

Q 2.8.1 Rigorous NDT methods are needed for the insert (P. 766). Are these methods available, described, qualified and already tested ? Where is this documented?

See response to Q 2.5.1.

Q 2.8.2 The plug design is not completely determined, whereas the understanding of its evolution seems rather empirical. On what basis can SKB claim that plugs meeting the requirements will be industrially feasible?

Comprehensive testing of the plug design is ongoing, and a full scale test of the actual design features will be performed in 2012-2013 at Äspö hard rock laboratory. The test will include full scale testing of the special rock excavation techniques and the concrete construction and grouting methods developed for the plug. All utilized construction procedures are considered to be standard industrial methods available on the market, and to be of robust and feasible design. SKB objective with the full scale test is to verify that all plug requirements can be fulfilled.

The full scale test will include pressurizing of the plug up to 7 MPa for normal operation mode purposes and up to 10 MPa for ultimate strength requirements, and the structural behaviour as well as the leakage passing the plug/rock interface will be thoroughly observed on long term basis with the planned monitoring equipment. The full scale test will give results on possible water tightness to be obtained, and if the leakage requirement is not fully met by the standard cement grouting method according to plan, more complex grouting methods utilizing other advanced grouting materials will be developed.

Q 2.8.3 Demonstrators and prototypes: Is there a document presenting the components needing further development and testing, and presenting the detailed planning for these tests? In particular, are the knowledge gained and the planning of future experiments in the Aspö laboratory presented in a comprehensive way?

The plans for further research, development and demonstration are presented in appendix VU (Operation, management and control – construction of the final repository facility) to the license application. This document is in Swedish but most of the planned work is described in the RD&D Programme 2010 (TR-10-63, sections 8-15 for technology development and section 17-26 for research on long term safety). The detailed planning of each experiment or demonstration test is made successively in accordance with SKB's quality management system.

Results from SKB's RD&D work are presented in the RD&D programmes (see TR-10-63). Äspö HRL results are presented in annual reports (see e.g. TR-10-10).

Q 2.8.4 Is it planned to have specific monitoring of some (or more) deposition tunnels to verify that the predicted evolution (saturation, absence of piping...) is effective? Is this described and planned in detail in a document?

Currently there are no such specific plans. As stated in section 5.8.3 a control program will be developed prior to excavation, with the objective of ensuring that the design premises and other requirements on the construction work and on the operations are fulfilled. Regarding the rock the aim of this programme is more focused on establishing feasibility of constructed but not yet used deposition tunnels and deposition holes, than to afterwards confirm their performance.

Hydrogeological modelling

Q 2.8.5 What is the justification of the choice of the semi-correlated DFN model? Different arguments are given in different places (especially P. 350 where it is only said that the uncorrelated model does not fit empirical data, but nothing on the correlated one). Could a comprehensive argumentation be presented?

See the response to Q 2.4.3.

Q 2.8.6 How was the base case of the DFN model chosen, among the 11 realisations of the probabilistic model? The concern is that this base case leads to less canister failure (0.087) than the mean of the realisations (0.12) (see P. 533). But, is this significant?

First, it is noted that only the ten additional realisations are equiprobable; i.e., the so-called single Base Case realisation differs from the additional ten in that it has deterministic properties of the deformation zones. Second, when compliance is assessed, it is the ten equiprobable realisations (with higher mean of canister failure) that are used.

2.8.2 Scenarios

Corrosion scenario

Q 2.8.7 In the scenarios, the correct application of EFPC is considered for granted (P. 599). In a pessimistic assessment, should not a failure in the implementation of this criterion, for a certain period during the exploitation, be considered?

As mentioned in the Main report (p. 473, 767) and extensively argued for in R-06-39, the FPI criteria (FPC and EFPC, see TR-10-21 for details) are pessimistic in the sense that it is assumed that large fractures are anonymous to geophysics and other investigation techniques. Additionally, most fractures fulfilling the criteria (roughly 80%, see details in TR-10-21) are not sufficiently large to impose any threat to long term safety. We anticipate that the ongoing programme for detailed underground investigations will provide means to lessen or eliminate the risk that traditional mapping accidently fails to identify potentially critical fractures, at the

same time provide means to utilise deposition holes, erroneously disqualified by EFPC due to its inherent conservativeness. See also response to Q 2.5.5.

Q 2.8.8 Why is the reference evolution described with the base case DFN model, whereas the corrosion scenario is evaluated with a set of realisations of the model? This leads to some confusion for the reader. Is the base case included in the realisations used to calculate the mean value?

Not all uncertainties are covered in the reference evolution and these unaccounted-for uncertainties are explored in the scenarios, in accordance with the established methodology for SR-Site. Hence, the corrosion scenario explores uncertainties associated with the stochastic nature of the DFN model, among other things. The base case is not included in the realisations since the base case model differs somewhat from the model used in the additional realisations, see further the first part of the response to Q 2.8.6.

Q 2.8.9 Could SKB present a table similar to Table 10-26 for each of the realisations of the DFN model (11 for the semi-correlated, 6 for the uncorrelated, 6 for the correlated), presenting depositions where advective conditions occurs, and failure time? Is it still true in all cases, as for the base case (see P. 533), that these failures require the highest sulphide concentration to occur before 1 Ma?

A table similar to Table 10-26 for the different realisations is being extracted from the results of the corrosion calculations. It will be delivered as a separate file by Sept 15 2011. (There is some additional information in the table since it also provides a response to Q 2.8.10.)

As seen in the table, in some of these realisations, a few more data points than the highest sulphide concentration cause failures. Such sensitivities are explored in section 12.6.2 subheading "Quantitative sensitivity analysis of canister corrosion", see Figure 12-17 and associated text on p. 607.

Q 2.8.10 Could SKB present (for example in an XL form) the breakdown of the probabilistic calculations for the three Figures 13-17, 13-26 and 13-27? More precisely, could SKB list the realisations of the probabilistic calculation contributing to the pulses observed, and present for each the details of the features causing the pulse:

- concerning the realisations and input data associated (e.g., realisation of the DFN model, concentrations...)
- concerning failure positions and time associated
-

It is not fully clear to us what the reviewer is asking for. We assume that the term "pulse" in the question refers to the entire release curve and not to the pulse like features forming a minor part of the curves. We are delivering a table (see response to Q 2.8.9) of all DFN realisations contributing to the releases in the three mentioned Figures with the following data:

- **DFN realisation number**
- **Deposition hole ID (i.e. failure position)**
- **Flow rate at deposition hole**
- **Sulphide concentration**
- **Calculated canister failure time**
- **Far field transport resistance in flow path connecting deposition hole to surface, *F***
- **Advective travel time for the flow path, *tw***

In the table, the following rows contributed to the results in the three Figures mentioned in the question:

- **Rows 15-70 (called "Semi, rxx"): Figure 13-17**
- **Rows 105-236 (called "Corr, rxx"): Figure 13-27**
- **Rows 269-422 (called Uncorr, rxx): Figure 13-26**

(There are also results for base case realisations for each of the models, provided as part of the response to Q 2.8.9.)

Each of the rows in the table was used in a number of realisations of the radionuclide transport models where fuel dissolution and nuclide specific data were sampled from distributions specified in the Data report. This data is not delivered since we understood that this was beyond what was asked for. Also, such a complete data set is quite large (and would require some additional post processing to be put in a format suitable for this review).

Records and memory and future human actions

Q 2.8.11 With respect to memory: are the measures that are planned, to transfer memory of the repository, described in a document?

See response to Q 2.5.28.

Q 2.8.12 With respect to the drilling case: The assessed impact of this case is very high, and seems unacceptable with regard to the health protection references. As it is mentioned, the assumptions are clearly unrealistic. As a result, no conclusion can be drawn from this scenario. Why is not a refinement of the assumptions presented, more realistic but still pessimistic, to assess this scenario?

Firstly, it should be noted that some of the figures reported are not correct. The calculated dose rate to a member of the drilling personnel should be 130 mSv/hour and not 500 mSv/hour as reported on page 748. Similarly, the dose rate reported for the case when 3% of Ag-108m is brought to the surface is wrong. The calculated dose rate should be about 4 mSv/hour and not 15 mSv/hour as stated on page 748. (The SR-Site FHA report, TR-10-53 gives the correct figures.)

Despite these errors the calculated dose rates are indeed high due to very pessimistic assumptions. There are possibilities of developing an assessment based on less pessimistic assumptions but this has not been made.

(It is also noted that, as argued in section 14.2.5 of the main report, the likelihood of this scenario is very low and that it is per definition not to be included in the risk summation.)

2.8.3 BAT

Q 2.8.13 On P. 763 it is stated: "Since the calculated risk is below the regulatory limit, the selected copper thickness is deemed adequate from the point of view of BAT". Is the fact of being below the regulatory limit considered as a criterion for BAT?

Strictly speaking the reviewer is correct, BAT is considered in addition to risk, so calculated risk could not be a criterion for BAT. However, what is meant to be said is that even significant increases (i.e. doubling the thickness) only lead to marginal risk reductions for a case where the assessed risk is already very low. Combining this with the observations that i) current thickness has been proven to be technically feasible to achieve and handle, ii) the dramatically increased cost of a much thicker copper and iii) the unknown technical complications of a significant thickness increase, are the main argument for judging current thickness to be BAT.

2.8.4 Other

Q 2.8.14 Can SKB provide the document quoted on P. 54 in English (or at least a summary), presenting how the conclusions from former reviews have been considered?

This is provided as a separate document, to be delivered by Sept 15, 2011.

Q 2.8.15 Can SKB provide the document SKB 2010b in English (or at least a summary), presenting the program for detailed investigation?

The document (R-10-08) contains a one page English summary. Translation of the entire document to English is in progress and is expected to be completed by the end of October 2011.

2.9 Questions from IRT Member 9

These questions are based on a review of TR-11-01

2.9.1 Reference scenario, initial state

Canister and insert

Q 2.9.1 What are the bases for the statement (P. 167) that no more than 600 grams of water will be left in the canister? What are the bases for the implication that if less than 600 grams of water is left in the canister, no degradation will occur?

The maximum of 600 g water left in the insert is a design premise (SKB TR-09-22) which is confirmed as initial state on page 167. Water left in the insert would corrode the cast iron, but with a maximum of 600 g water the corrosion depth would be negligible, see further the Fuel and Canister Process report (SKB TR-10-46, section 3.5.1). The 600 g is estimated from the pessimistic assumption of one water filled fuel pin per fuel element.

Q 2.9.2 In Table 5-8 on page 168, is the value for niobium content of the PWR cladding correct?

All the values in Table 5-8 (taken from an early version of Table 2-5 of Spent fuel report, SKB TR-10-13, and not corrected according to the published version) are erroneous. We thank the reviewer for noticing the error and will include the correct values for Table 5-8 in the errata list. Table 5-8 should be the same as in the published version of SKB TR-10-13, i.e.:

Table 5-8 The content of N, Cl, Ni and Nb in the construction material for typical BWR and PWR fuel assemblies.

	Weight in 1 fuel assembly (kg)						
	BWR Svea 96 Optima 2				PWR Areva 17x17		
Element	Cladding	Other	Fuel channel	Total	Cladding	Other	Total
N	0.002	0.002	0.005	0.009	0.0055	0.0058	0.011
Cl		0.000006	0.000008	0.000014	0.000003	0.000014	0.000017
Ni	0.02	1.1	0.86	1.99	0.27	2.19	2.46
Nb		0.0082	0.0008	0.0091	1.08	0.09	1.17

Q 2.9.3 At the bottom of page 170, SKB states that for an isostatic load, the margins of NDT methods for detecting critical flaw sizes are adequate to make the probability of missing critical defects low.

Are asymmetric loads also possible? If so, would the NDT methods for asymmetric loads be equally reliable?

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. Permanent asymmetric loads may occur due to uneven density distribution of the saturated buffer due to irregularities in the geometry of the deposition holes. The resulting bending stresses in the cast iron insert are in all considered cases lower than the yield strength.

The canister properties and design parameters that are important for loads from uneven pressure from the bentonite buffer are in principle the same as for the isostatic load case. One additional requirement, however, is based on circumferential crack-like defects in the insert. The acceptance level is not too demanding since defects with up to 48 mm depth can be accepted. Such defects are not at all expected to occur in the manufacturing process.

The calculations verify that the canister strength is sufficient to withstand the uneven pressure from the bentonite buffer (TR-10-14 section 4.11.3).

Q 2.9.4 It is unclear why the units for the probability of detection using the current NDT methods (p. 171) are in millimetres. Please explain.

The value that has been used for probability of detection is the "$a_{90/95}$", which means that defects of a certain size will be detected with 90% probability within a confidence range of 95%, i.e. the level of uncertainty in the determination of detection capacity, see TR-10-14 appendix B. The values specified in p. 171 indicate the defect sizes that will be detected by 90% probability.

Q 2.9.5 On page 171, SKB states that deviations in the copper canister thickness that would reduce the canister thickness below 45 mm could be "detected with the naked eye" such that the probability of a canister having a thickness less than 45 mm is considered "negligible". Does SKB plan to use visual measurements to identify deviations from the design canister thickness below 45 mm?

SKB plans to have accurate measurement systems to verify that the canister components will have required dimensions. The value 45 mm comes from the case that either the measurement system due to some malfunction or some operator mistake leads to a component with dimensions outside the tolerances. If this happens there are several steps where this big deviation will be detected, for example that the components will not fit to each other. See further TR-10-14 section 5.3-5.5.

Q 2.9.6 Table 5-9 on page 172 provides information on the design thicknesses of the copper canister wall along with the distribution of canisters with walls that are somewhat thinner than the design value. In the first part of the table, the fraction of canisters with a wall thickness between 45 and 47.5 mm (e.g., 1.5 to 4 mm narrower than the design tube thickness of 49 mm) is stated to be a "few per thousand". In the lower half of the table, the fraction of the canisters with thicknesses 10 to 20 mm lower than the design value is stated to be "one per thousand". Are these numbers consistent?

The values in the table express two different scenarios; the first part predicts the global variations in thickness while the second part predicts local reductions due to defects. The latter value is more precise as the numbers are based on a thorough analysis of the welding process that is considered to have the highest risk for defects that could reduce the copper wall thickness.

Q 2.9.7 On page 173 SKB notes that "eight tubes and twenty lids" were inspected, using NDT methods. Is the distribution of the canister thicknesses found in Table 5-9 on the previous page based on these 28 tests?

SKB has not done any systematic measurements of the copper wall thickness after machining, i.e. the table is not based on these inspections. Regarding defects in the copper components, only a limited number of defects have so far been detected by the non-destructive testing. This indicates that the occurrence of defects will be limited and due to the design of the manufacturing processes the most probable defects will be oriented in the direction perpendicular to the corrosion path. See further TR-10-14 section 5.3-5.4.

Q 2.9.8 On page 176 and again on page 177, it is stated that a key design premise is "a nominal copper thickness of 5 cm, also considering the welds." If so, then please explain the difference between the value stated on page 176 and the design value of 48.5 mm for the "welds" in Table 5-9 on page 172.

The design premise of 5 cm is the rough value given from the SR-Can safety assessment. The reference design in Table 5-9 is the more detailed design drawing measure that also has been verified for the production process. The copper thickness used in the corrosion analyses in SR-Site is described in the answer to Q 2.9.9. In the updating of the Design premises after SR-Site the more detailed measures of copper thickness will be considered.

Q 2.9.9 Please confirm that for the purposes of canister failure estimates, the design values shown in Table 5-9 are used rather than the 5 mm value stated on pages 176 and 177.

The copper shell thickness used in the corrosion analyses is 47 mm for the eroded buffer situation, while the corrosion from other corrosion processes are compared with the copper thickness of 5 cm. In the latter analyses the corrosion is at a maximum a few millimetres, which is much smaller than the initial copper thickness and no failures are expected. The derivation of a copper thickness to use in the analyses is discussed in the Data report (SKB TR-10-52, section 4.1) and further in the Corrosion calculations report (SKB TR-10-66, section 4.3.4). This is also partly an answer to Q 2.9.8.

Q 2.9.10 The statement at the bottom of page 177 implies that SKB plans to measure the temperature on the surface of the canister after emplacement. Please confirm if this is correct, and if so, provide the means of measurement and the period of time the measurements will be conducted.

No, the text refers to the handling and transportation before emplacement.

Q 2.9.11 What are the bases for the design criteria of an exposure rate maximum of <1.0 Gy/h on the canister surface (pg. 178)?

Gamma irradiation of moist air in the canister-buffer gap leads to formation of nitric acid, which may cause corrosion of the copper. Earlier analyses gave 1 Gy/h as an upper limit for the radiation outside the canister, why this was set as the design criterion (SKB TR-09-22, section 3.1.5). The analysis of corrosion at an initial dose rate of 1 Gy/h is found in the Fuel and Canister Process report (SKB TR-10-46, section 3.5.4).

Buffer, backfill, plug

Q 2.9.12 When will the design of the plugs, shown schematically in Figures 5-22 (page 197) and 5-24 (page 199), be completed?

See the response to Q 2.8.2.

Q 2.9.13 On page 576, SKB states that the allowed variability of the composition of the selected buffer materials "will be defined at time of purchase of the buffer". Please explain why the allowed variability cannot be decided now?

Different suppliers/mines may offer materials that are different, while still meeting all the requirements. This may refer to composition of accessory minerals, composition of the counter ions, etc. It will be easier to define an allowed variability for those parameters when the source is known.

Q 2.9.14 Should there be a Ca/Na ratio criterion for the bentonite buffer? Should the criterion be a range of values between which a buffer material would have the right combination of swelling properties without being too stiff so as to transfer rock shear forces to the canister? It is also noted that the Ca/Na ratio affects sorption properties (page 578).

The Ca/Na ratio will be conditioned by the groundwater at the site. This is especially true in wet canister positions. A criterion would therefore not make much sense.

Q 2.9.15 On page 426 it is stated "models indicate that the plug is saturated rapidly." SKB claims that the assumption of slow plug saturation is "pessimistic". Assuming the plug is designed similar to that shown in Figure 5-22, could there ever be a case where the hydraulic pressure to the left of the plug in this figure could exceed the pressure on the right? If so, the plug may become dislodged. Has this been considered?

Yes, that is not unlikely to happen. However, the purpose of the plug is to maintain the pressure in the deposition tunnel. If the pressure in the transport tunnel is higher, no performance of the plug is needed.

Q 2.9.16 The Ca/Na ratios of the two bentonite materials provided in Table 5-10 (page 180) are potentially significantly different. On page 398, SKB states "the maximum free swelling of the bentonite is strongly dependant on the *valence* and concentration of the ions in the interlayer space." [emphasis added]. Since the Ca/Na ratios of the two bentonites are different, are the same design criteria used for both types of bentonite? If so, why? If not, what are the separate criteria?

In the repository the swelling will be confined. The free swelling is a minor concern. As seen in Figure 5-14 the swelling pressure as a function of dry density is almost identical for both materials except at very low density.

Q 2.9.17 Table 5-11, page 181, provides the design criteria for the solid and ring-shaped blocks and the bentonite pellets – along with the accepted variation in the criteria. SKB notes at the bottom of the same page that the statistical variation of the solid and ring-shaped blocks shown in Table 5-11 (page 182) are based on measurements of 10 ring-shaped and 15 solid blocks. Table 5-12 provides one standard deviation and 99.9% confidence interval values. It is noted that the 99.9% C.I. value for the ring-shaped block density slightly exceeds the design value. Are the values in Table 5-12 based on sample sizes of ten and 15? Also, are the values in Table 5-12 for MX-80 or Ibeco bentonite? Are the same design criteria (Table 5-11) and variabilities (Table 5-12) used for both MX-80 and Ibeco bentonites?

The 99.9 C.I. value for the ring shaped blocks is 2.088 kg/m^3, which is within the design value of 2.070±20 kg/m^3. The values in Table 5-12 are based on the same sample sizes of ten and 15. The blocks were manufactured from MX-80 bentonite. The criteria are based on a bentonite with ~80-85% montmorillonite, there should be no significant difference between MX-80 and Ibeco RWC in that respect.

Q 2.9.18 Please explain the differences in the 99.9% C.I. numbers in Table 5-13 (page 183) from the 99.9% C.I. values in Table 5-15 (page 186). It is also noted that the first three entries in the 99.9% C.I. column in Table 5-15 are slightly below the design criterion of >1950kg/m^3. Is this acceptable?

The values in Table 5-15 are calculated with the assumption of rock fall-out from spalling in the wall of the deposition hole. This is discussed in more detail in the Buffer Production Report. Densities below 1,950 kg/m^3 can only occur locally and if there has been a rock fall out resulting in an increase of the pellet filled gap of at least 30 mm to in total 80 mm. Based on current results this can be expected in about 400 deposition holes out of 6,000. However, there are alternative ways to warrant the conformity of the installed density in all parts of the cross section to the design premises even if there has been a rock fall out, these are:

- **to adjust the installed buffer mass to the actual deposition hole geometry by selecting or manufacturing blocks with high density for the sections where the rock fall out occurs,**
- **to reduce the variation in width of the pellet filled gap by adjusting the placement of the buffer blocks in deposition holes where rock fall out occurs.**

If these kinds of correction actions are judged to be unfeasible, either the acceptable variations in deposition hole geometry or in bulk density of blocks and pellets must be reduced.

In summary it can be concluded that the initially deposited buffer mass most probably will correspond to a saturated buffer density of 1,950–2,050 kg/m^3. However, to warrant this, the buffer blocks cannot be randomly selected in deposition holes with rock fall out.

Q 2.9.19 A "Milos Backfill" will be used for the backfill (page 188). How do the properties of the Milos Backfill compare to the MX-80 and Ibeco bentonites that are planned for the buffer, and how do the property differences relate to the design criteria for the Milos Backfill compared to the MX-80 and Ibeco buffer bentonites?

The "Milos Backfill" or IBECO_RWC-BF is a lower quality bentonite than the buffer materials. The basic difference is a lower montmorillonite content. However, the difference in the hydro-mechanical properties is small at relevant densities.

Q 2.9.20 Row "Bu23" in Table 7-4 (page 230) refers to a montmorillonite density at saturation of 1650 kg/m^3. Earlier in this volume a number of 1950 kg/m^3 was referred to. Please clarify why the 1650 number applies for transport.

1950 kg/m^3 is the lowest density in the reference design. 1650 kg/m^3 is the safety function indicator criterion for when colloid mediated transport of radionuclides in the buffer needs to be considered. This is discussed further in section 8.4.3.

Q 2.9.21 On page 304, it is unclear what "a value of 10% is used *as an example* in SR-Site" means related to water saturation of the plug and its sealing ability.

10% refers to how much of the total void volume within a deposition tunnel that will leak out through the plug. However, a value of 20% is used in the piping/erosion estimate.

Q 2.9.22 On page 309, it is stated that "[T]he plug design will under all circumstances be adjusted to meet the requirements and failed plug performance is not assessed in SR-Site." What technical bases does SKB have to have confidence that, indeed, the plug can be designed for all reasonably likely eventualities?

The sealing ability of the plug is only needed during the operational period of the repository. No sealing ability is needed when the main and transport tunnels have been backfilled. This means that the sealing ability of the plugs can be monitored for their entire service life. If a plug would fail, it can be repaired.

Q 2.9.23 SilicaSol is to be used to grout boreholes if cement-based grout “is unsuitable” (page 367). This must mean SKB has not yet determined whether cement-based grout will work. When and how will this be decided? It is also not clear what a “grouting hole” is. Does SKB mean small fractures, or the grout-filled portion of fractures, or boreholes, or something else?

The Scandinavian countries have a long experience with successful grouting with cement products in fractured, crystalline rock. The successfulness relies however on the grain size of the cement. As a rule of thumb, the capability to seal a fracture with a specific mean aperture requires the d_{10} to be roughly 4 times smaller than the aperture. This is a limitation in the low conductive rock mass at depth in Forsmark.

Below the level of the top seal, at least 100 m above the deposition areas, only grouts with pH<11 will be used, to ensure the stability of the buffer and backfill clays.
SKB has carried out full scale grouting trials with Silica Sol at the 450-m level at Äspö HRL. The experiences are very promising. Currently, the use of primarily SilicaSol for grouting at the repository level is the main alternative, due to better penetrability in fractures with low aperture, as well as the chemical composition. Final decisions if grouting using SilicaSol would be needed – or if cement based “low pH” grout would be sufficient can only be made based on the practical experiences gain at depth in Forsmark, e.g. during the excavation of the repository access.

Grouting hole = borehole used to inject grout.

Q 2.9.24 On page 373, please confirm that a “fast” and “slow” tunnel means a tunnel in which the groundwater flow rate is “fast” and “slow”, respectively.

The terms refer to the saturation time for the tunnel – which is strongly related to the groundwater flow rate.

Q 2.9.25 Figure 10-52 on page 375 presents the results of calculations on the swelling pressure for various pellet slot sizes. While it is clear what the pressure in the pellet slot and the block is, please clarify how the “total” swelling pressure is derived for this figure.

“Total” refers to a homogenized case with the same initial density in the entire deposition hole. This is clarified in the reference.

Q 2.9.26 In Figures 10-57 and 10-58, the legends refer to “(Avg. 75%)”. Please explain what this means.

Extrapolated output database values at nodes common to two or more elements are averaged conditionally. Abaqus/CAE averages values at nodes common to two or more elements when the contributing elements lie in the same result region. If the relative nodal variation for each node included in the plot is less than the averaging threshold, values of contributing elements are averaged at that node. If the relative nodal variation exceeds the setting, the values are not averaged. The percentage shows how many per cent of the nodes that have averaged values.

Q 2.9.27 Figures 10-65 (page 393) and 10-66 (page 394) provide results of calculations on the evolution of calcium and sodium as a function of position and time in two different buffer materials.

It would be beneficial to see a side-by-side comparison of Na and Ca concentration evolutions for the MX-80 and the Ibeco bentonites using the *same* water saturation time (one short and one long), so the effect of the Na/Ca ratio between the two bentonites can be determined if the behaviour of the two types of bentonite was similar enough to *not* cause significantly different colloid stability behaviours between the two types of bentonite. Is such a comparison available?

Figures 5-15 (identical to 10-65) 5-20 and 5-21 in /Sena et al. 2010, TR-10-59/ can be used for such a comparison. For the case with high flow the sodium concentration in the exchanger is ~41% for the MX-80 and ~34% for the Ibeco bentonite after 10,000 years. The difference is mainly related to the content of dolomite in the Ibeco material.

Q 2.9.28 Figure 10-69 (page 398) shows the calculated influence of temperature on the stress-strain behaviour of the two different types of bentonite. Strain behaviour of the Ibeco bentonite may be significantly different for the two temperatures considered (20°C and 150°C). None of the curves shown, however, are for the peak buffer temperature criterion of 100°C. Are plots of the behaviour at 100°C for each bentonite type available? Also, SKB states that the difference in the shear properties between 20°C and 150°C are „not very prounounced". Visually, the shear properties in the right figure in Figure 10-69 look different. What assessment was done to allow SKB to conclude the difference between 20°C and 150°C shear properties was „not very pronounced"?

The reference /Dueck 2010/ contains results from field experiments in the temperature range of 90-110 °C. The brief presentation in the main report of SR-Site is too limited to draw the conclusion that the "effect is not very pronounced". However, /Dueck 2010/ contains a vast number of results and it can be seen that the effect of a temperature increase from 20 °C to 150 °C gives a similar change in properties as an increase in density with a few tens of kg/m^3.

Q 2.9.29 Table 10-8 provides a summary of the results from calculations of sensitivity analyses of the chemical composition of two different bentonites[2] - one of which is a heretofore unmentioned „Deponit CA-N" bentonite. Is this a third bentonite type that may be used in the buffer or backfill? If so, where are the results for the Ibeco bentonite?

Deponit CA-N is identical to Ibeco RWC – the supplier changed the name during the work with SR-Site. Table 10-8 is copied from /Sena et al 2010/ where the old name was used.

Q 2.9.30 In the discussion of the interaction of a degraded bottom plate and the buffer on page 411, was there consideration of the effects of the plate corrosion products that have a higher specific volume than the plate itself?

The effect on an expanding plate would be negligible on the properties of the buffer.

Q 2.9.31 On page 431, line 4, SKB uses the word „backfill". Does SKB mean „buffer"?

No, the saturation of the backfill is compared with the saturation of the buffer.

Deposition hole (borehole) acceptance criterion EFPC

Q 2.9.32 Please explain what the three colours mean in Figure 10-5 on page 295.

Green: Natural fractures. Yellow: Blast-induced fractures. Red: Blast fractures

[2] The table states the results are for the evolution of the composition of the groundwater, but the text on page 405 implies the results in Table 10-8 are for the two buffer materials in the presence of a "typical" Forsmark groundwater.

Q 2.9.33 Please provide the transmissivity units in the legend for Figure 10-6 on page 296.

The unit is (-) (dimensionless) since the figure provides relative transmissity (e.g. as change of transmissivity in relation to the "virgin" transmissivity of the intersecting fracture).

Q 2.9.34 On page 306 an empirical equation is used to determine the accumulated mass of eroding bentonite in deposition holes. Since the equation is empirical, did the erosion test upon which this equation must be based cover a sufficient range of conditions that may be expected during the evolution of the repository under the credible scenarios considered?

It should be noted that piping only occurs as long as large hydraulic gradients are present. It is therefore not a process that needs to be considered in very long time frames. A number of erosion tests have been performed in different geometries. All parameters of interest have been varied. That covers water chemistry, flow rate, injection pressure, flow direction (vertical/horizontal), different materials, duration of test, etc.

Q 2.9.35 In the middle of page 309, it is noted that the swelling pressure beneath the bottom plate "should not be allowed to reach [0.2 MPa]". What methods will SKB use to ensure this will not happen?

This requirement only concerns the feasibility of installation and is not related to long-term safety. Furthermore, in the now ongoing system design of the buffer a promising solution is to move to a design without a bottom plate. Then this requirement will no longer be needed.

Q 2.9.36 The text near the bottom of page 326 states "no information can be given regarding how the loss of canister positions is distributed…". Yet Figure 10-8 (page 302) implies that for at least one criterion, the particular loss of locations could be determined. Under what circumstances can or cannot the distribution of the loss of canister positions be determined?

Figure 10-8 shows deposition hole positions rejected due to inflow rejection criteria for a certain realisation of the hydrogeological model. Similar pictures could have been produced for positions lost to other criteria (e.g. primarily the FPC/EFPC for all fractures). However, these are simulation results and other realisations of the DFN model will show different locations that would need to be rejected. The simulations do, however, illustrate the percentage of positions to be rejected even if the locations are currently unknown. The actual decision whether to reject or not can only be taken after detailed characterisation is made from the vicinity of the deposition tunnel, e.g. based on pilot hole and mapping of potential deposition tunnels. This is clearly outlined in the detailed characterisation programme (SKB R-10-08 in Swedish; an English translation is expected in the end of October 2011).

The text on page 326 deals with the thermal evolution. Since we are concerned with high temperatures, we make, in the thermal analysis, the (somewhat) pessimistic assumption that no canister position is lost. However, the overestimation of the highest temperatures in the repository is judged to be quite small, since most canister positions are indeed judged to be accepted.

Fuel properties

Q 2.9.37 Will future fuel properties be the same as summarized on page 20?

In p. 20 are summarized the fuel types and amounts to be deposited based on the fuel inventory already in Clab and a reference scenario which accounts for the future spent fuel originating from the operation of the Swedish power plants. Fuel properties for the whole fuel inventory, including expected future spent fuel according to the reference scenario, are discussed in more detail in the Spent fuel report (TR 10-13).

Before new fuel types are allowed to be used in the Swedish reactors an assessment is made of their potential impact on the safety of the final repository.

2.9.2 Long term performance

Performance assessment models

Q 2.9.38 Figures 7-3 and 7-4 (pp. 242, 243) are the assessment model flowcharts for earlier and longer-term periods of time. There is an arrow connecting "radionuclide transport, far-field (TR-10-50)" in yellow to "doses (TR-11-01)". Should the two be connected via the LDF values?

The way this is expressed in the flow chart is indicating that the determination of doses is dependent on both the results of the modelling of radionuclide transport in the far-field and of LDF values.

Transport resistance

Q 2.9.39 For the case of unsealed boreholes discussed on page 352, it is stated that 23% of the particles in the particle tracking model come out the unsealed borehole, which seems quite a lot of the entire flow. Yet SKB also notes this does not have much effect on the performance measures. Are these „performance measures" ones that only relate to the flow field, or is there also no impact on overall assessed dose rates in the performance model?

The performance measures (PMs) are defined on page 339 of TR-11-01 and are discussed in more detail in R-09-22 (Section 3.4.4). These measures depend on the flow field and hydrogeological properties only; i.e., transport conditions such as e.g. matrix properties do not affect the PMs. However, the PMs (specifically F) do have a strong effect on final calculated dose.

The reason that the unsealed boreholes do not have a great effect on the PMs is that the majority of particles released from deposition hole positions do not go through the boreholes. As noted in the text, if only boreholes that do have paths going through boreholes are considered, the effect is larger (but still within a factor of four).

Q 2.9.40 Figure 12-3 on page 579 points out that the "semi-correlated" case results in less advective positions than either the uncorrelated or fully correlated cases. It seems somewhat arbitrary, then, the particular amount of correlation that is used as the base case. Please explain why this particular "amount" of semi-correlation was used as perhaps any other value of correlation would result in more advective positions.

See the response to question Q 2.4.3.

Colloid formation/ Buffer erosion

Q 2.9.41 The last sentence on page 357 states that the real groundwater composition variability will likely be larger than captured in SKB's uncertainty assessment. Please assess whether this might have an impact on overall repository performance. For example, if there is a possibility that the ionic strength could be lower than the assessed uncertainty range, could this have a significant impact on buffer stability?

There is always an uncertainty in simulations, and because the simulations discussed here have not been performed using pessimistic assumptions, for example concerning ionic strength and calcium concentrations, one can not rule out the theoretical possibility that in reality some deposition hole might experience waters outside the ranges given for example in Fig.10-39.

However, comparing the "real" calcium concentrations shown in Fig. 10-38 and the statistics for calculated calcium concentrations in the repository volume shown in Fig. 10-40 for 2000 AD, one can see that all analysed [Ca] values are above 0.015 mol/L. The chance of having waters below this level at present at repository depth seems rather small, not only based on the data, but especially when considering the conceptual hydrogeochemical model of the site, discussed in detail in report R-08-47. In contrast, the calculated values in Fig.10-40 of the SR-Site main report show about 5% of the calculated present-day with [Ca] values below 0.006 mol/L.

The statement made in the SR-Site report is based on the theoretical arguments that one can not rule out "anomalies", but the modelling results show a wider variation of groundwater composition than the variability experimentally observed at the site. Because of this SKB feels confident that the modelling results overestimate the real variability in groundwater chemistries.

Q 2.9.42 The last line on page 358 says "*above* this limit". Should it read instead "*below* this limit"?

No. Montmorillonite colloids are *not* stable at cation concentrations above 4 mM. The sentence appears to be correct in the report.

Q 2.9.43 Regarding the safety function of the minimum charge equivalent of 4 mM, it is stated on page that calcium is the "most important" cation. Does this have an implication about the similarity or dissimilarity of the MX-80 and Ibeco bentonites as the two have potentially significantly different calcium contents?

The Ibeco bentonite may seem to have advantages at first glance. However, the composition of the exchanger will be conditioned by the composition of the groundwater. This is especially true if the water flow is relatively high. This means that the composition of the bentonite in contact with the water bearing fracture will be fairly similar independent of the initial composition. Dilute groundwaters are often high in pH, which means that the calcite content of the Ibeco bentonite will be insoluble and not contribute to the dissolved calcium concentration.

Backfill erosion

Q 2.9.44 In the first bullet on page 529 SKB states that the amount of erosion will be the same for each of the eight glacial cycles over the one million-year assessment period. Has SKB considered the possibility that the erosion rate might differ for successive glacial cycles?

Yes, this is considered in the analysis of the buffer advection scenario, section 12.2. See in particular the sub-heading "Global warming variant and other climate cases" in section 12.2.2.

Q 2.9.45 SKB states "the conceptual model for quantifying the extent of erosion is associated with uncertainties that are difficult to quantify." (page 580). What approach did SKB use, then, to deal with erosion uncertainty?

The approach, taken in the buffer advection scenario, section 12.2, was to consider a bounding case where advective conditions are assumed to prevail throughout the assessment period in all deposition holes, see further the subheading "Bounding cases" in section 12.2.1. This case is also the basis for the risk summation underlying the compliance demonstration.

Q 2.9.46 On page 702, SKB notes "there is no reliable method" to quantify the effect metallic iron will have on montmorillonite stability. How, then, will SKB address this issue?

This becomes an issue only when a copper shell is failed so that the cast iron insert may contact the buffer. For the corrosion scenario, canister failures only occur in cases where a significant part of the buffer is already eroded away, rendering further negative impacts on the buffer irrelevant. For the low probability of canister failures due to shear movements, a bounding case where the buffer functions are lost 10,000 years after failure cover both buffer degradation due to iron-bentonite interactions and due to erosion. (This is explained at the bottom of page 702.)

Plug

Q 2.9.47 The top paragraph on page 306 states that it is not known how tight the plug can be made, but that it is assumed that "20% of the total volume of the tunnel will leak out through the plug". Also on page 309, SKB states "The plug design will under all circumstances be adjusted to meet the requirements and failed plug performance is not assessed in SR-Site." What are the bases for SKB's confidence that the plug design can be so adjusted?

See the response to Q 2.8.2.

Copper Corrosion

Q 2.9.48 In several places in TR-11-01, such as on page 528 and 575, SKB estimates that 23 deposition holes will have "advective conditions" by the end of one million years. Other discussion in the report evaluates the possibility of oxidizing and/or "dilute" conditions occurring in some deposition holes. Might the deposition holes experiencing "advective conditions" be the same holes experiencing oxidizing or dilute conditions? Based on the first bullet on page 605, SKB states there is no correlation because the boundary conditions are different. This requires additional explanation.

Dilute conditions are a prerequisite for buffer erosion so these two phenomena are always correlated. Deposition holes modelled to have advective conditions at some point in time have thus experienced dilute conditions for an extended period of time.

The first bullet on page 605 states that the boundary conditions for the extreme case of ice sheet location yields oxygen penetration in a few depositions holes and that neither of these are among those were advective conditions are calculated to occur for boundary conditions prevailing in the long-term and that control the extent of buffer erosion. This is the result of the calculation of these phenomena with the same hydrogeological model and with relevant boundary conditions for the two cases. This indicates that the correlation is weak.

Criticality inside a failed canister

Q 2.9.49 On page 646 SKB states that the k-eff ≤ 0.95 criterion can be met for irradiated (rather than fresh) fuel. SKB also states on this page that acceptance criteria have been defined "to ensure that the fuel assemblies shall not, under any circumstances, be encapsulated if the criticality criteria cannot be met…" Please provide the bases for both of these statements.

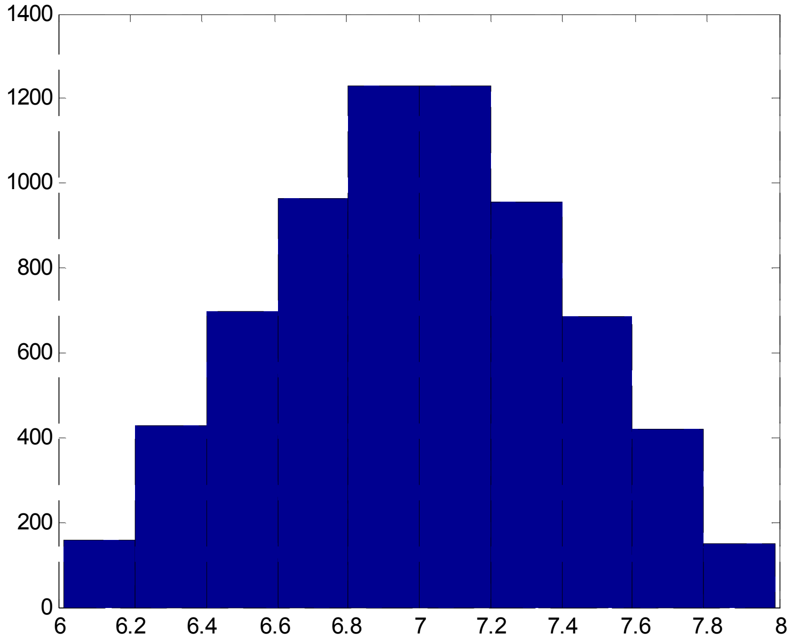
This is described shortly also in p. 166, section 5.3.4 of the main SR-Site report and in more detail in the Spent fuel report (SKB TR 10-13, sections 3.1.2 and 6.7) and the Fuel and canister process report (SKB TR-10-46, section 2.1.3),

Fuel dissolution rate

Q 2.9.50 Table 7-2 (page 223) states that "residual gas radiolysis/acid formation" inside a failed canister is "not relevant". Please explain.

Residual gas radiolysis/acid formation is a process which occurs immediately after canister sealing (SKB TR-10-46, section 2.5.2), due to radiolysis of water and traces of air in the Ar filled canister. In an intact canister residual oxygen, water and radiolytically formed nitric acid will be consumed in about 100 years by corrosion reactions with the canister insert. The process is considered not relevant for a failed canister, since at the expected times of canister failure the oxidants have already been consumed and the canister is expected to fail through corrosion from outside.

Q 2 9.51 The fuel dissolution rate uncertainty/variability is quantified as a log-triangular distribution (page 661). Is there a plot of this distribution? For the probabilistic analyses, is the entire range of the distribution sampled?



The above histogram shows the log fuel dissolution *time*, the variable used by the model rather than the dissolution *rate*. (This histogram is part of the final data control performed for the radionuclide transport calculations according to the SR-Site quality assurance plan described in Section 2.9 of the Main report. The crude binning of the figure is done by the code used in the final control and does not reflect the resolution of the input distribution.)

The entire range of the distribution is sampled in the radionuclide transport calculations.

Biosphere

Q 2.9.52 On page 644, SKB states that it is using the central parts of Öregrundsgrepen rather than newly drained organic soils. SKB has also stated that newly drained soils would have the highest contamination levels and could still be productively farmed for 50-100 years, which is one to two lifetimes. Why has SKB elected to use the central parts of Öregrundsgrepen rather than newly drained organic soils?

The landscape dose conversion factor (LDF) used in the safety assessment captures the consequences of draining and cultivating the most contaminated wetland at the worst possible time. That is, in the simulation the consequences of draining and cultivating each contaminated wetland at all possible points in time has been evaluated, and the LDF represents the maximum over all biosphere objects and simulation time points (see "Assumptions on human behaviour and land use" p 634-635, and "Landscape dose conversion factor" p 636 for details).
Page 644 sorts under section 13.2.6 "Uncertainties and cautiousness in the risk estimates". The assumptions of human behaviour and land use is discussed in specific on page 644, and the approach used in the safety assessment (i.e. cultivation of newly drained peripheral organic soils) is contrasted by a more realistic scenario (given modern land use practice and the configuration of a future landscape). From this discussion it is concluded that the land use scenario used in the safety assessment is cautious.

Q 2.9.53 What is a "provisional" biosphere FEP (Page 96, Section 3.3)?

In the SR-Can FEP catalogue, a provisional biosphere FEP was defined for each subsystem of the biosphere with the only purpose to serve as a "heading" to which FEPs in the NEA FEP database relevant to the biosphere could be linked. These provisional FEPs were introduced as a temporary solution awaiting the definition of processes for the biosphere which was not completed within the work with SR-Can. For SR-Site, biosphere processes have been defined and corresponding biosphere FEPs have been included in the SR-Site FEP catalogue and all the earlier provisional FEPs have been deleted. This means that the SR-Site FEP catalogue does not contain any provisional FEPs. All NEA FEPs that were linked to the provisional biosphere FEPs in the SR-Can FEP catalogue were revisited and linked to the relevant SR-Site biosphere FEPs.

Permafrost/repository depth

Q 2.9.54 In Table 10-27 on page 551, "Buffer backfill borehole seals", "Freezing of closure material" "12.4" row, should the last column of this row be "Can 3" rather than empty?

No, this cell should be empty. The closure material is that used at the top part of the repository shaft; freezing of this material is expected and poses no threat to the canister (or any other safety functions).

Isostatic load

Q 2.9.55 Row "C10" in Table 7-3 (page 226) states that stress corrosion cracking of the cast iron insert in a failed canister has been neglected. Please provide the basis for this.

Nitrate could cause stress corrosion cracking in the cast iron insert, provided tensile stresses are occurring. The possible formation of nitrate (nitric acid formed by radiolysis of nitrogen gas left in the insert) is reduced by exchange of the air in the insert with argon, before the copper lid is welded. Analyses also show that only small areas would have tensile stresses. The handling of this process is described in the Fuel and Canister Process report (TR-10-46), section 3.5.3.

Earthquakes

Q 2.9.56 On page 467, SKB states "estimates of anticipated earthquakes at Forsmark … are associated with some yet unresolved uncertainties and fundamental assumptions." One of aspect of the EFPC criterion is that "fractures with radii exceeding 225 m are avoided in deposition holes." (page 472) However, the text does not provide a description how fractures of this size are to be detected.

The text refers to Cosgrove et al 2006 (R-06-39) and SKB 2010b (R-10-08, in Swedish; an English translation is expected by the end of October 2011) in which arguments for the detection of such structures are brought forward. In short, we argue that the larger the fracture, the less is the likelihood for the fracture to be geologically or geophysically anonymous. Fractures with radii of 225 m (≈ 160 000 m^2) most probably constitute minor fracture zones. As such they most probably display sufficiently clear characteristics to be identified during underground construction and investigations. As a matter of fact, we argue in Cosgrove et al (2006) that most critical fractures are not anonymous but, as it is not possible to *prove* that we can identify *all*, we cautiously assume that all fractures smaller than 225 m (radius) are indeed blind to geophysics, though identifiable by means of FPI criteria.

Q 2.9.57 It seems possible that earthquake motion could cause significant changes in the groundwater flow rates and directions, thereby mobilizing colloids. In row "Bu18" in Table 7-4 (page 229) it is stated that montmorillonite colloid release during earthquakes was "not specifically treated". Please explain what this means and justify why it was not specifically treated.

The table describes the handling of the colloid formation process as such, which is unaffected by an earthquake. The consequences of the combination of buffer erosion and shear movement are discussed in section 12.9.3. Erosion does have an impact on radiological consequences if a shear failure has occurred, while an already eroded buffer decreases the risk for shear failure. Shear movements that do not lead to canister failure do have a small impact on the overall buffer erosion.

Q 2.9.58 It seems possible that local shear forces during an earthquake could damage the grouts that may be used in places throughout the repository. Row "Ge17" in Table 7-6 (page 237) states that degradation of the grout during earthquakes is "not relevant". Please explain why.

This issue concerns chemical degradation of grout and the safety related aspect is that the degradation products will have a negative effect on pH. Grouting has no function for long-term safety so the physical loss of grout is not a safety concern.

2.9.3 Analysis of scenarios

Screening of scenarios

Q 2.9.59 It is unclear what is meant by screening out a scenario if it is of "little intrinsic significance" (page 221). Please explain.

As stated on page 221, the bullet list exemplifies reasons for neglecting an influence, and not for screening out a scenario. An influence only defines the coupling between a single process and the selected variables that define the state of the system. Neglecting an influence because it is of "little intrinsic significance" means that there is a physical dependence between a process and a variable, but that the impact on e.g. the process of a change in this specific variable is negligibly small for the process in question. For example, the influence of a change in temperature on the process diffusion is of little significance in the temperature range expected.

Q 2.9.60 On page 568 paragraph above section 11.2.3, and then again in the last paragraph, SKB mentions indicators that are not associated with a criterion. They say “the criterion was assessed to be *violated* [emphasis added]”, but “violated” against what criterion? Perhaps what is meant is that SKB simply carries along the numerical value of those safety indicators into the quantitative scenario analyses? Please clarify.

It is not clear what the reviewer refers to. Regarding indicators without a criterion, the statement in the paragraph above section 11.2.3 is “*If the indicator is not associated with a criterion, or if the criterion was assessed to be violated in the reference evolution, then it is evaluated if the value of the safety function indicator could be less favourable for safety than is the case in the reference evolution.*” In the last paragraph, no statement on indicators without a criterion is made.

Q 2.9.61 Table 11-1 (page 570) provides the results of the scenario selection process. SKB notes the red cells are deviations from the main scenario conditions. The last row of the table is for the “unsealed repository” scenario. As the unsealed repository case is a deviation from the main scenario, it is unclear why all of the boxes in this row are not red. Please explain.

The scenario differs from the main scenario only in certain aspects and these aspects are marked in red.

Analysis of scenarios

Q 2.9.62 The two paragraphs above Section 11.3 on page 569 are an example of lumping deposition holes into just two groups: (1) “a single deposition hole”; and (2) “all (or many) holes”. From a risk perspective, it may be important to assign probabilities to failure of specific numbers of deposition holes, e.g., P(1 failure); P(2 failures); P(3 failures), and so on to create a probability distribution function for the number of deposition holes that have failed. This is because the consequence of “X” holes failing may be “X” times the consequence of one hole failing. If so, then in the probabilistic risk assessment, it may be important to be able to multiply the probability that “X” holes are failed times the consequence of that many holes failing. By lumping the scenarios into just two categories (1 failure; >1 failures) it is unclear whether this approach can be carried into the probabilistic risk assessment properly. Please confirm that only two groups of deposition hole failure probabilities were used and, if so, justify lumping the number of failures into just two categories.

No, we do not lump into only two groups. This would be incorrect for the reason the reviewer suggests. Rather, the number of affected deposition holes is determined in relevant cases and the consequences for all affected holes are added.

The sentence causing the question is probably “*In some cases it is relevant to consider both the probability that a single deposition hole is affected and the probability of all (or many) holes being affected.*” The intention was to distinguish between local and global failure modes. This could be relevant in e.g. the isostatic load case where a high isostatic pressure from a thick ice sheet above the repository could affect a large number of canisters (global failure) whereas a manufacturing flaw weakening the load-bearing canister insert would affect only a single canister (local failure). (The sentence could in fact be omitted.)

Rock shear scenario

Q 2.9.63 Calculations of the potential for rock shear on page 481 consider the buffer material properties for just a Ca-bentonite. Is a Ca-bentonite the limiting form of bentonite with respect to transmitting rock shear to the canister?

The use of the Ca-bentonite in the analyses is specified in the design premises (SKB TR-09-22), which builds on the earlier safety assessment SR-Can (SKB TR-06-09). The stress-strain relation for Na- and Ca-bentonite have been measured (SKB TR-10-32) and used to formulate the material model (SKB TR-10-31) that is used in the shear modelling (SKB TR-10-34). The material model report (TR-10-31) concludes the use of the Ca-bentonite material model is slightly conservative with respect to shear movement. Also, given the groundwater composition at Forsmark, an initial Na-bentonite is expected to develop into a Ca-bentonite in a relatively short time.

Q 2.9.64 The external conditions involved in the rock shear scenario are provided in two bullets on page 618. Should there be a third bullet that says something like "Glacial load changes" along with appropriate discussion in the text?

Glacially induced earthquakes are powered mainly by tectonic stresses, but triggered by endglacial instability (argued in the Geosphere process report, TR-10-48, e.g. Section 4.1.3, p. 88). The glaciers can thus reactivate faults if, and only if, the zones are critically stressed by background stresses (steered by the strain rate). However, once in place, and if sufficiently thick, the continental glacier promotes seismic stability. Thus, the impact of continental glaciers on the long term perspective essentially regards the timing of earthquakes. There is always a probability for intraplate earthquakes without any impact of continental glaciers, the longer the time frame, the higher the probability. For instance, the 1000 year scenario handles earthquakes that are not correlated to (future) glacial load. We therefore judged it appropriate not to include any specific bullet regarding changes in glacial load.

2.9.4 Sensitivity analysis

Q 2.9.65 Since many of the variables in the sensitivity analyses have been fixed rather than considered as uncertain, the sensitivity analyses presented in TR-11-01 would not, by definition, detect the potential importance of uncertainty in the fixed variable on the overall results. What analyses have been done to assess the potential impact on the risk analyses for these fixed variables for which SKB acknowledges that the values of the variables are uncertain?

Information of this nature is compiled in Table 13-13, section 13.10.1. As seen in the table, most factors that are not treated probabilistically are handled in a pessimistic way. For some of these factors illustrative variant cases with less pessimistic data have been calculated, but in most cases it is only stated that further knowledge allowing a less pessimistic handling would reduce the calculated risk.

Q 2.9.66 It is unclear whether the assessment that 23 deposition holes experiencing advective conditions is a fixed number or the mean of a distribution. Please clarify. If the latter, is the distribution carried into the probabilistic assessments?

It is a fixed value, obtained in the erosion calculation for the reference evolution, where only one realisation of the hydrogeological DFN model is used and all other data are deterministic, see section 10.3.11. In the further analyses in the erosion scenario, section 12.2.2, a number of additional cases are considered and in each case several hydrogeological realisations are used as input, each yielding a fixed value. For each case, the minimum, maximum and mean values taken over the realisations are presented in Figure 12-3. The result of each realisation is then propagated to the corrosion calculations in section 12.6.2. Here, the entire distribution of sulphide concentrations is sampled for each deposition hole with advective conditions, yielding canister failure times for the highest sulphide concentrations. From these results a mean number of failed canisters is determined, see Figure 12-16. From the corrosion calculations, the entire set

of failure times and positions where corrosion failures are calculated to occur is propagated to the probabilistic consequence calculations, for a set of relevant corrosion cases.

Q 2.9.67 Similarly, SKB states it used the mean value of [HS^-] "for all deposition positions" (page 603) rather than a range of values from an uncertainty distribution. Given that higher [HS^-] concentrations could lead to canister failure by corrosion, please justify the exclusive use of the mean rather than a distribution of [HS^-] concentrations.

No, this is not stated. The mean value is only used in a sensitivity case to illustrate the effect of assuming that temporal variation would, in the long term, yield an average sulphide concentration that would be reflected by the mean value. In all other cases, sulphide concentrations are sampled from the sulphide distribution. See further the discussion on p. 603, and the results of the sensitivity cases on p. 607-608.

Q 2.9.68 The dominant radionuclide contributing to dose is Ra-226. What are the factors that contribute to Ra-226 being the dominant contributor to dose? Are there uncertainties that might cause another radionuclide to dominate the contribution to total dose rate?

For the failure modes contributing to risk, the dominance of Ra-226 is quite pronounced at one million years, both in the near-field and far-field releases, see e.g. the results of the deterministic central corrosion case in Figures 13-15 and 13-16. (Further deterministic cases are given in the Radionuclide transport report, TR-10-50.) If the "true" K_d-value for Ra in rock would be the highest of the values covered by the epistemic uncertainty reflected in the K_d distribution, this could mean that the dominance of Ra would be less pronounced. It would still be one of the most significant nuclides since the maximum K_d-value is only about a factor of 5 higher than the mean value (Table 6-89 of the Data report, TR-10-52) and since the transport related F-factor in the affected deposition holes are large, rendering sorption a less effective retention mechanism.

Q 2.9.69 Please explain why the "peak of the means" is "more difficult to interpret".

Is the reviewer referring to the statement "*The "peak of the mean" interpretation is meaningful in the sense that all exposure pathways to hypothetical individuals living in the future are considered whereas the "mean of the peaks" concept is more difficult to interpret.*" in section 2.6.2? It is thus claimed that the mean of the peaks is more difficult to interpret. This is due to the fact that the peaks will occur at different times and an averaging of them would thus not reflect a mean exposure to a given individual which is required for a risk calculation. (This has also been established in earlier dialogues with the former authorities SKI and SSI, now merged to SSM.)

Q 2.9.70 Has SKB used "horsetail plots" (plots of individual realizations all in a single figure) to provide a graphical representation of the distribution of dose versus time outcomes?

No, this has not been used in SR-Site.

2.9.5 BAT

Q 2.9.71 When assessing BAT, it seems SKB has only considered whether the BAT option can reduce releases or doses from the repository. There appears to be no assessment of the potential for increasing near-term risks by use of a BAT meant to reduce long-term risk. For example, the repository is designed to avoid peak bentonite temperatures above 100°C using a specific set of "techniques" (design features), such as canister size, disposal hole spacing, etc. Construction, loading, and transportation of canisters, construction and loading of tunnels and disposal holes also have near-term risks primarily to workers, but also to the public to a lesser extent. Presumably, the more canisters that need to be constructed, loaded, and transported to the site, and the more tunnels and deposition holes that need to be constructed, the higher the near-term risk to workers and the public will be. Hence, in this example, while altering the design "technique" to allow for higher bentonite temperatures runs the risk of increased long-term doses, the near-term risk, by having to use fewer canisters, tunnels, and deposition holes, may be reduced. When evaluating BAT options, has SKB considered the impact on near-term risks as well as long-term risks of each BAT option? Also, is cost a factor in evaluating BAT?

In the design work the main focus has been on minimizing risk both for the operational and the post closure period. Since the risk during the operational period is assessed to be very low no conflicts between operational and post closure safety has been identified and we consider the technique selected to be BAT as far as can be judged at this point. However, as the detailed design and implementation work continues, such a conflict could at least in principle arise. For future safety assessments we therefore plan to further enhance the integration between operational and post close safety assessment allowing for an even deeper overall assessment of the details of system.

As a general rule decisions for selecting a certain technique are primarily based on safety and feasibility, i.e. only techniques that can realistically be achieved and that provide sufficient safety can come into consideration. If there is more than one technically feasible option the technique offering most safety would be selected, where safety is considered both in terms of potential impact on risk and what is judged to be the more robust option. If differences in safety are judged marginal, the technique judged to be more feasible and economical is selected. (See also response to Q 2.5.34).

Q 2.9.72 SKB notes on page 82 that in cases where there is considerable uncertainty in calculated risks, priority should be given to the use of BAT. Throughout TR-11-01 SKB notes many pessimistic assumptions and values of variables were selected due to the large amount of uncertainty regarding processes or variable values. Did SKB consider the substitution of BAT instead of using pessimistic assumptions or values for each of these cases?

BAT concerns selection of technique, not how safety is assessed. However, in principle we agree that application of too many pessimistic assumptions could lead to obscuring a potential safety benefit of one technique over another. For this reason, we aim for a probabilistic assessment, rather than a pessimistic assessment, when this is possible. However, safety is not only a matter of calculated risk. Selecting techniques that are more "robustly" safe than one that potentially is "safer" but where the arguments are more uncertain, is in SKB's opinion a good safety culture.

Q 2.9.73 Given that the use of "design premises" is to limit the number of design choices, is the use of design premises and BAT compatible?

Both BAT and the use of "design premises" are required by regulations or suggested in guidelines to regulations. That aside, we see no conflict in this. Care is needed to consider all words in the BAT acronym - and not only focus on "best". Most of technical design work actually is a matter of finding a solution that works at all (i.e. at technique that is – or can be – available). For the latter issue, working with Design premises as a means for defining the requirements on the technique to be developed is essentially a necessity. Selection between techniques is only needed in case there already exists different techniques or if the development work finds several solutions that are able to solve the problem. In these cases we certainly select the technique that appears to provide the safest performance – and in case safety differences are marginal – the technique appearing to be the most practical and economical. (See also response to Q 2.5.34).