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2012:39

Review of Engineering Geology and Rock Engineering aspects of the construction of a KBS-3 repository at the Forsmark site – Initial Review Phase

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SSM perspektiv

Bakgrund

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

Projektets syfte

Uppdraget är en del i SSM:s granskning av aspekter inom Ingenjörsgeologi och Bergteknik i SKB:s ansökan om slutförvaring för använt kärnbränsle i Forsmark. Uppdraget avser granskning av integriteten för bergmassan som omger det tilltänkta KBS-3 slutförvaret med fokus på uppförande av anläggningen och dess konsekvenser för det initiala tillståndet samt utvecklingen av förhållandena i närfältet. Kommentarer ges om teknikerna för bergmassans kartering och karakterisering, anläggningens layout, borrning, sprängning, bergutschaktning samt injektering i kristallina bergarter.

Författarnas sammanfattning

Övergripande tycker granskarna att den geomekaniska datan insamlad och konsoliderad hittills är imponerande i mängd och kvalité. Insamlad data har integrerats i sammanlänkade analyser för att kunna studera slutförvarets utveckling under uppförande och drift. Dock finns det ett antal osäkerheter gällande data och analyser som är oundvikliga när man hanterar geologiska material. En insats har gjorts för att förstå påverkan och fortplantning av osäkerheter på analyser och projektering. Däremot finner granskarna att den största bristen i rapporteringen är avsaknandet av ett konsekvent sätt att hantera nivån av tilltro för olika slutsatser som är grundläggande för valet av projekterings förutsättningar. Ytterligare farhågor utöver datan samt dess tolkningstydlighet är:

- Utmaningar resulterande från motstridiga krav från å ena sidan snäva toleranser under uppförande och drift samt å andra sidan den geologiska variabiliteten och osäkerheten som förekommer på flera skalor.
- Medan tillräcklig detaljeringsnivå samt tilltro erhålls för parametrarna gällande de dominerande bergarterna finns det fortfarande utrymme för utökad datainsamling eller tolkningsmöjligheter för mindre frekventa men förekommande bergarter i slutförvarsvolymen.
- Det finns farhågor om att kriteriet för att godta placeringen av depositionshålen (EFPC) inte tar hänsyn till interaktionen mellan spjälkning och befintliga sprickor i berg. Konsekvensen skulle kunna vara ett större bortfall av deponeringshålspositioner än förväntat.
- Betydande osäkerheter finns angående de initiala bergspänningarna. Trots att detta är förväntat för djupa anläggningar som slutförvaret, är ett mer konservativt antagande nödvändigt för spridningen av de förväntade bergspänningar som använts för analysen av bergskadezonen uppkommen från tunneldrivningen (EDZ)

- Observationsmetoden föreslås som metod för hantering av utföranderisker. Emellertid finns det behov av att förtydliga hur avvikelser från det förväntade utfallet kommer att hanteras samt huruvida metoden kommer att underlätta för den prompta anpassningen av projekteringen till oförväntade förhållanden.

Projektinformation
Kontaktperson på SSM: Flavio Lanaro
Diarienummer ramavtal: SSM2011-3641
Diarienummer avrop: SSM2011-4336
Aktivitetsnummer: 3030007-4017

SSM perspective

Background

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

Objectives of the project

This project is part of SSM's review of SKB's license application for final disposal of spent nuclear fuel at Forsmark and covers issues of Engineering Geology and Rock Engineering. The assignment concerns review of the integrity of the rock mass surrounding a KBS-3 repository with focus on the construction and its effects on the initial state and performance of the near-field conditions. Review comments concerning the techniques of rock mass characterization, facility layout, drilling, blasting, withdrawal and grouting in crystalline rocks are also provided.

Summary by the authors

In general, the reviewers find that the level of geomechanics data collected and synthesized to date has been impressive in scope and high in quality. The data collected has been incorporated into interlinked analyses concerning construction and operational performance of the repository. There are a number of uncertainties in the data and subsequent analyses that are unavoidable when dealing with earth materials. An effort has been made to understand the impact of propagation of these uncertainties through the analysis and design process. The reviewers find, however, that the main shortcoming of the reporting is a lack of coherent structure required to understand the relative reliability of the conclusions central to the design premises. Major concerns beyond data and interpretive clarity include:

- Challenges posed by conflicts between very tight construction and operational tolerances and the geological uncertainty that is likely to create geometric variability at different scales.
- While significant detail and confidence exists for the main rock types expected, there is room for additional data or interpretation concerning less common but likely rock types within the repository footprint.
- There is a concern that the rejection criterion for the Deposition Holes (EFPC) may not adequately incorporate the interaction of spall damage and existing fractures and that the rejection rate may be higher in practice than proposed.
- Significant uncertainty exists with respect to the in-situ stresses. While this is to be expected for deep projects such as this, conservatism is required at this stage with respect to adopted ranges for stress within the context of EDZ (Excavation Damage Zone) generation around excavations and deposition holes.

- The Observational Method is proposed to deal with uncertainties. There is a need to be clear about how deviations will be dealt with and whether this approach will facilitate adequate and timely adjustments to the design as deviations from expected conditions are encountered.

Project information

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Review of Engineering Geology and Rock Engineering aspects of the construction of a KBS-3 repository at the Forsmark site – Initial Review Phase

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Contents

1. Introduction

This Technical Note is a revised version of that submitted on the 25th of June, 2012. This review covers the integrity of the rock mass surrounding a KBS-3 repository for spent nuclear fuel with focus on the construction and its effects on the initial state and performance of the near-field conditions. Specifically, the engineering geology and rock mechanics are analyzed concerning the techniques of rock mass characterisation, excavation and grouting in crystalline rocks. The layout and stability of the excavations in relation to the geological conditions are reviewed, together with any issues arising from the layout and geometrical tolerances of the repository, need for rock reinforcement, and excavation-induced damage (EDZ) and spalling (excluding thermal-induced). Also reviewed are the assessment of the *in situ* and induced stress fields as well as the need for rock mechanics testing and monitoring during construction of the repository.

In general, the reviewers find that the level of geomechanics data collected and synthesized to date has been impressive in scope and high in quality. In addition, the data collected has been incorporated into interlinked analyses concerning construction and operational performance of the repository. There are a number of uncertainties in the data and in the subsequent analysis that is unavoidable when dealing with earth materials. An effort has been made to understand the impact of propagation of these uncertainties through the analysis and design process.

The reviewers find, however, that the main shortcoming of the reporting to date is a lack of coherent structure to maintain a clear picture of this propagation and to understand the relative reliability of the conclusions central to the design process (i.e. occurrence of subordinate rock types, expected rock stresses, expected rock behaviour, rock thermal properties, sufficiency of the rock volume for disposal). In most cases this is really an issue of clarity rather than actual oversight.

Major concerns beyond data and interpretive clarity include:

- Challenges posed by conflicts between very tight construction and operational tolerances and the geomechanical uncertainty that is likely to create geometric variability at different scales.
- While significant detail and confidence exists for the main rock types expected, there is room for additional data or interpretation concerning less common but likely rock units within the repository footprint.
- There is a concern that the rejection criterion for the Deposition Holes may not adequately incorporate the interaction of spall damage and existing fractures and that the rejection rate may be higher in practice than proposed.
- Significant uncertainty exists with respect to the *in situ* stresses. While this is to be expected for deep projects such as this, conservatism is required at this stage with respect to adopted ranges for stress within the context of EDZ generation around excavations and deposition holes. The ranges selected for further analysis should be widened to account for the impact of larger stresses, within the range suggested by the original data, and a range of directional stress ratios.
- The Observational Method is proposed to deal with uncertainties. There is a need to be clear about how deviations will be dealt with and whether this approach will facilitate adequate and timely adjustments to the design as

both moderate and fundamental deviations from expected conditions are encountered (i.e. extended occurrence of rock spalling, large water in-flows, significant stress anomalies, branching structure of some deformation zones).

2. Main Review Findings

2.1. Gaps/Omissions

Potential issues examined for which we could not find sufficient details in the SKB reports reviewed include:

1. There does not appear to be a Deposition Hole rejection criterion that considers a non-persistent fracture intersecting a Deposition Hole that connects with continuous EDZ/spalling along the floor of a Deposition Tunnel (or vice versa). Continuous EDZ should be treated jointly with the fracture intersection scenarios described in the EFPC.
2. The EFPC criteria only allows for fracture extent as mapped, not for the possibility that the fracture may propagate/coalesce during subsequent construction/operation activities in response to further stress changes and increasing rock temperatures.
3. It does not appear that a project cost-schedule risk assessment has been carried out with respect to construction. A qualitative risk assessment is reported with respect to geohazards, however, schedule delays and cost overruns should also be considered.
4. A fully demonstrated testing of the loading of the canisters at full weight and for the buffer geometry/tolerances specified would be required as a proof of concept with respect to constructability. Repeatability of the procedure should be included to determine the percentage of successful completions per attempt.
5. Means to verify conformance to the Design Premises in a construction environment have yet to be developed for a number of the premises. Much will depend on how characterization and monitoring data is implemented during construction. Licensing conditions should consider the limited Quality Assurance (QA) plan included in the License Application.

2.2. Need of Clarifications by New Submissions

Requests to SKB for complimentary information include:

1. The assessment of likelihood of encountering sub-horizontal brittle fracture zones at the repository depth does not appear to be considered in the qualitative risk analysis. This appears to be based on the identification of only three gently dipping deformation zones in the Site Descriptive Model. Clarification is requested as to the resolution of the detection methods used (seismic reflection, single-hole interpretations) with respect to the minimum sub-horizontal deformation zone detectable.
2. Is the exclusion of Deposition Holes in low thermal conductivity rock included in the Deposition Hole acceptance/rejection criteria? Do the analyses of loss of Deposition Hole positions account for the likelihood of amphibolite lenses occurring more frequently than indicated?
3. What methodology will to be used to reliably characterise less common rock types (e.g. amphibolites lenses, vuggy granite, etc.) in near-field during construction?
4. Clarification is requested as to the mechanism by which the trend of the maximum horizontal stress is interpreted to decrease in gradient at 400 m depth while the trend of the minimum horizontal stress remains linear.

5. Are the stresses measured in boreholes KFK001/DBT1 and KFK003/DBT3, which are located outside the target volume and in FFM04, applicable to the repository volume? How would the stress interpretation change if these data were excluded?
6. Clarification is requested with respect to the conclusion that EDZ, if it develops, will not be continuous. Is the Äspö experiment on which this conclusion is based only applicable to blast-induced damage and not excavation-induced damage resulting from the redistribution of stress and stress concentrations?
7. Clarification is requested as to the source and basis for the 40 m centre-to-centre separation distance between Deposition Tunnels. This appears to be based on thermal dimensioning. Have stress analyses been performed that consider the influence of excavation sequencing on the development of stresses around/between the Deposition Tunnels and boreholes as the repository is constructed? The analyses reported appear to be based on the stresses between multiple Deposition Holes in a single Deposition Tunnel.
8. Is the 30-35% overbreak limit expressed in the *Design Premises* for Deposition Tunnels excessive or incompatible with the requirement to minimize construction damage? Can this be reduced to improve overall quality control? If the specified total volume and section area overbreak limits are maintained, then the reviewers recommend adding a third linear limit to ensure local exceedance is minimized. For example: "Acceptable largest linear overbreak (measured normal to design profile) should not exceed the nominal 0.25×Radius for a circular profile or 0.13×Span for a square profile".
9. The potential for adverse effects from blasting on the deposition works are accounted for in the repository layout by imposing separation and safety distances. Are similar considerations required for other vibration sources, for example heavy vehicles carrying heavy canisters or hauling waste rock along uneven surfaces?
10. Clarification is requested as to the risk associated with having the ventilation passing from the deposition areas into the excavation areas (as required by the Linear Development Method sequencing) in the event of an accident involving a canister. Is this a potential issue identified in the risk assessment of worker safety or in the development of safety protocols?
11. Clarification is requested as to references in the construction plan reports to the use of a "TBM". Is this in reference to a tunnel boring machine?
12. Clarification is requested as to the strictness of the Deposition Hole and buffer installation tolerances. How critical are they to the safety case? Can they be modified to allow for slightly greater tolerances in order to improve the success rate of installation? If critical, would it be better to install the canister and buffer blocks together as an integrated package allowing the integrity of the full engineered barrier to be verified before installation in the Deposition Holes?
13. Is there a limit on the amount of overbreak that occurs in the Deposition Holes? Should overbreak be included in the Deposition Hole acceptance/rejection criteria?
14. Clarification is requested as to the role of water inflow acceptance criteria for the different excavation types with regards to the Design Premises and Safety Functions. Similarly, what long-term function, if any, is the grout expected to play.
15. Updates are requested as to the long-term performance of low pH and silica sol grouts together with tested procedures for their handling and use.

16. Clarification is requested as to whether the analysis that concluded spalling is unlikely in the Deposition Tunnels due to their orientation relative to that of the stress field also considered spalling occurring at the tunnel face.

2.3. Need of Clarifications by Discussion

Questions/topics that we believe require a more detailed discussion with SKB include:

1. A detailed discussion regarding plans to develop contingency actions in response to adverse ground conditions, if encountered, may be beneficial. Clarification as to how these will couple *Design Premise* requirements with worker safety and construction cost requirements should be established.
2. Some of the uncertainties to be managed by the Observational Method will not be resolved until after construction and operations are well underway (e.g. presence of adverse geology/fractures in the farther reaches of the repository). What are the implications if the rejection ratio of Deposition Holes doubles (triples) in the planned second half of the repository from experiences in the first half of the repository when options for adapting are significantly more limited?
3. A single unified summary of the combined set of measurements, analyses and assumptions (including filtering logic) for the determination of the *in situ* stress regime (trends and ranges) needs to be compiled. The current documentation is complex and leads to the risk of overly confident stress specifications.
4. A discussion would be beneficial regarding the selection of the representative *in situ* stress and associated ranges (likelihoods) at the repository horizon, as well as provisions for follow-up refinement and implications for design of realistic deviations from this base case (both deviations from the average predicted stress field and local stress anomalies).
5. The distinction and separation of construction damage (CDZ) from stress-induced excavation damage (EDZ) should be discussed, especially with respect to the mitigation and management measures proposed (smooth wall blasting). Also to be considered is the excavation fracture zone (EFZ), also referred to as the highly damaged zone (HDZ).
6. Would installing the canister and buffer blocks together as an integrated package negate the need for the bottom plate? A discussion would be beneficial regarding the sensitivities of the rock/buffer and buffer/canister interfaces with respect to the *Design Premises* and *Safety Functions*.
7. A discussion would be beneficial regarding the construction challenges and implications for worker safety in placing restrictions on the use of shotcrete. Clarification is required as to quantifying what “continuous” means in the context of the Design Premises and how sensitive the reference design for the Deposition Tunnels is to the use of shotcrete.
8. A discussion would be beneficial regarding whether a connected EDZ, in the event one develops along the walls of a Deposition Hole or in the floor of a Deposition Tunnel, should be treated as a fracture in the same way other large fractures are considered in the EFPC? The treatment of interconnected fractures that intersect and connect the respective (potential) EDZs of the Deposition Hole and tunnel are not discussed in the EFPC.

2.4. Further Review

Subject matter we suggest requires further review to be carried out during the subsequent Detailed Review phase includes:

1. Further review may be required as to the likelihood and impact of increased width and/or change in position of the major deformation zones on the reference design and underground layout design with respect to increased impact of respect distances within and around the deposition area.
2. Further review may be required as to whether increased tectonic disturbance and poorer rock mass conditions than accounted for can be expected along the western margin of the repository, and what impact this may have on the constructability and safety of the transport tunnels and ventilation shafts.
3. Further review may be required as to the spalling strengths adopted, the corresponding uncertainty, and whether this should be considered as an uncertainty/geohazard in the qualitative risk analysis of site uncertainties on design. If so, this uncertainty should be considered in tandem with the uncertainty regarding *in situ* stress.
4. Are there scenarios that the Observational Method won’t be able to react to in a manner that ensures worker safety, project economics and/or the Design Premises being met, and how do the options for adaptation change with different stages of repository construction and operations? Are there operational and post-closure considerations that cannot be tested through the Observational Method?
5. Further review may be required for the currently adopted stress regime at the repository location, including the impact of realistic deviations from this assumption coupled with the uncertainties in strength and stiffness (including local geological heterogeneities).
6. There is limited experience, both experimental and applied, with respect to time-dependent behaviour and long-term evolution of stress-induced brittle fractures. A more detailed and thorough review of the applicability of concepts relating to sub-critical crack propagation, stress corrosion and long-term strength degradation and performance of crystalline rock under sustained compressive loading on stress-induced fractures in the EDZ is suggested.
7. Further review may be required as to how the construction sequence factors into the geohazard risk analysis. The farther extents of the repository will not be penetrated by excavation workings until after 20 years of construction. How does this impact the overall risk of ensuring the availability of the required Deposition Holes if the geological conditions encountered are more adverse than expected? For example, would the construction of the Main Tunnels, Transport Tunnels and Short-cut Tunnels before proceeding to the construction of the Deposition Areas be a feasible measure to reduce uncertainties and confirm the design assumptions?
8. Further review may be required as to experiences with grouting in crystalline rock from deep boreholes. The challenges of pre-grouting continuously from surface to the repository depths may force an alternative to raise-boring to construct the ventilation shafts. A risk assessment and cost-benefit analysis should be carried out.
9. Further review should be carried out on the long-term performance of rock bolts, mesh, shotcrete and grout, and what implications their degradation will have on the long-term behaviour and stability of the excavations.

10. Further review should be carried out on the effectiveness and reliability of seismic and radar reflection (or other geophysical techniques) for detecting discriminating fractures in a construction/operations environment.

2.5. Independent analyses

Analyses we recommend be carried out during the subsequent Detailed Review phase include:

1. An independent assessment of the geohazard risks and their likelihood of occurrence may be required. This should possibly include an independent analysis of Deposition Hole rejection scenarios relative to one or more geohazard risks being realized.
2. An analysis of cumulative error propagation is required tracing assumptions and uncertainties in defined stress regime through EDZ assessment and support calculations.
3. Uncertainties in stress and spalling strength may combine to create a likelihood of stress-induced spalling. Quick scoping calculations within the ranges of uncertainties suggest spalling could be significant. This similarly extends to the uncertainties in thermal conductivity and coefficient of thermal expansion, which likewise may combine to increase the extent of thermal spalling.

3. Scope of the Initial Review Phase

This review covers the integrity of the rock mass surrounding a KBS-3 repository for spent nuclear fuel with focus on the construction and its effects on the initial state and performance of the near-field conditions and engineered barriers. Specifically, the engineering geology and rock mechanics are analyzed concerning the techniques of rock mass mapping and characterisation, drilling, blasting, withdrawal and grouting in crystalline rocks.

The layout of the excavation in relation to the geological conditions, excavation techniques and stability problems are also reviewed as items of key interest. This includes the review of any issues arising from the layout and geometrical tolerances of the KBS-3 repository, need of reinforcements, Excavation Damage Zone (EDZ) and spalling (excluding thermal-induced, as this is covered by another review assignment).

Also reviewed are the assessment of *in situ* and induced stress fields as well as the need for rock mechanics testing and monitoring during construction of the repository.

3.1. Assigned SKB Reports for Review

Review documents were organized according to: i) primary reports, encompassing those assigned as mandatory, and ii) secondary reports, including reports that were recommended in the review assignment together with other reports representing original sources as cited in the primary reports reviewed. These are listed in detail in Appendix 1. Those specified as mandatory and recommended in the review contract, "*Description of Review Assignment of SSM's Initial Review Phase for SKB's safety assessment SR-Site: Engineering Geology and Rock Engineering aspects of the construction of a KBS-3 repository at the Forsmark site*", are listed below.

3.1.1. Mandatory

TR-11-01, SR-Site: 4.1-4.5, 5.6-5.8, 10.2, 10.3. 5, 10.4.3-4, 15.5.12, 15.5.15-19, 15.6.2, 15.6.6-7, 15.7.4 and Errata
TR-10-12, Design and production: 3.5-3.9, 4.7-4.9
TR-10-52, Data report: 6.4, 6.5
TR-10-18, Design, construction and initial state of underground openings
TR-09-22, Design premises: 3.3-3.5
TR-10-48, Geosphere process report: 3.1, 4
TR-08-05, Site description: 5, 7
R-11-14, Framework for detailed characterisation for construction and operation

3.1.2. Recommended

R-08-113, Underground Design, Layout and construction plan
R-08-114, Underground Design, Grouting
R-08-115, Underground Design, Rock mechanics and rock support
R-08-116, Underground Design, Layout D2
R-05-71, Potential underground stability (wedge and spalling)
TR-10-21, Full perimeter intersection criteria

3.2. Covered Review Topics

The topics reviewed were based on those specified in the "*Description of Review Assignment of SSM's Initial Review Phase for SKB's safety assessment SR-Site: Engineering Geology and Rock Engineering aspects of the construction of a KBS-3 repository at the Forsmark site*". These were then expanded to include several sub-topics, listed in Table 1, to ensure thorough coverage of the assigned reports.

Table 1: Breakdown of review topics covered in this report.

Review Topics	Sub-Topics
Rock mass mapping and characterisation techniques	– Rock domains and fracture domains – Intact rock properties (incl. spalling strength) – Rock mass properties – Thermal properties – Use of 'Observational Method'
In situ stresses	– Measurement techniques – Interpretation – Validation of proposed stress model
Excavation layout in relation to:	– Geologic conditions – *In situ* stresses (repository depth) – Stability and ground control
Excavation techniques	– Drill & blast – Reaming of Deposition Holes – Geometries and tolerances
Excavation induced stresses:	– 3-D stress analyses and stress distributions – Stability (operational safety) – Reactivation of fractures (slip & opening modes) – Induced seismicity
EDZ & spalling (excluding thermal)	– Deposition Holes – Deposition Tunnels – Shafts and ramps – Overbreak/geometrical tolerances
Grouting	– Pre-grouting (shaft sinking) – Deposition Tunnels – Shafts and ramp
Shotcrete	– Ground control – Treatment of overbreak/geometrical tolerances
Reinforcement	– Safety during construction – Long-term performance – Excavation response following support degradation – Role of stray materials
Auxiliary structures	– Bottom plate in Deposition Hole – Deposition plugs – Reinforcement of tunnel plugs
Construction sequencing	– Linear development method – Impact of excavation works on engineered barriers
Investigation & performance verification during construction	– Testing – Monitoring

4. Findings of the Initial Review Phase

Review of SR-Site and the assigned reports for the Initial Review Phase focussed on their clarity and transparency, scientific robustness, data traceability (from site description through to interpretation and modelling), thoroughness in propagating data uncertainties and testing alternative conceptual models, and focus and substance in relation to the *Safety Functions*, *Design Premises*, site understanding and constructability of the KBS-3 repository at Forsmark.

Overall, we found the work produced in the reports to be of a high scientific quality. The investigations carried out, methodologies employed and analyses undertaken often push the boundaries of both the state-of-practice and state-of-the art in rock engineering. The documentation is substantial, but still highly accessible in its clarity and readability. Nevertheless, we did encounter several general issues with the documentation. Specifically:

- Original data and sources were sometimes difficult to track, due to referencing of a report that references a different report (and so on). This leads to poor traceability of some key arguments. This is particularly true for the *in situ* stress prediction.
- The *Design Premises* reported in the license application reports are not always consistent (compare TR-09-22, TR-10-16, TR-11-01). The *Design Premises* serve to specify the performance requirements of the repository. Obsolete premises should not appear in the license application.
- Secondary reports are cited that sometimes state their findings as being inconclusive but are used in higher level reports (e.g., SR-Site) as being conclusive. Examples include the *in situ* stress interpretation and analysis of EDZ and spalling potential.
- Sparse sample distributions or those with anomalies and outliers are sometimes not thoroughly reviewed (e.g., *in situ* stress data).
- Methods to ensure quality assurance in constructing the reference design too often appear as an afterthought.

These are discussed in the following sub-sections, which provide our review findings for the Initial Review Phase. The review is structured to report the key issues and questions that arise for each of the review topics (§3.2), focussing on aspects related to the engineering geology and rock mechanics that could potentially affect: i) the safety-related *Design Premises* (primarily based on those reported in TR-11-01), and ii) the constructability of the repository. These are then followed by our recommendations with respect to gaps/omissions, requests for clarification and further detailed review.

4.1. Rock Mass Mapping and Characterisation

4.1.1. Site Geology, Deformation Zones and Geological Uncertainty

<u>A. Review Comments Related to Design Premises</u>:

Relevant *Design Premises* discussed in SR-Site (TR-11-01) related to the site geology, rock domains and major deformation zones include:

- *The repository volume needs to be selected where it is possible to find large volumes of rock fulfilling the specific Deposition Hole requirements.*
- *Deposition Holes are not allowed to be placed closer than 100 m to deformation zones with trace length longer than 3 km.*
- *Deposition Holes should, as far as reasonably possible, be selected such that they do not have potential for shear larger than the canister can withstand. To achieve this, the EFPC criterion should be applied in selecting Deposition Hole positions.*

The feedback to these *Design Premises* suggests that the repository volume and depth selected are adequate (TR-11-01, §15.5.18), and that further detailed investigation during construction will allow for the actual extents of damage zones and splays related to the major deformation zones to be characterized at depth (TR-11-01, §15.5.12). It is also suggested that the EFPC criterion may be superseded by other means to identify the size of fractures intersecting the Deposition Holes if required. Nevertheless, TR-10-21 presents a thorough development and validation of the EFPC. The reviewers are confident that as it is proposed the EFPC is a practical criterion.

The identification of major deformation zones is well constrained by surface mapping and geophysical surveys and further supported by borehole logging, as reported in the Site Descriptive Model (TR-08-05, §5). Several open questions, however, may be posed that could impact the number of available Deposition Holes (due to constraints placed by the *Design Premises*). These are:

1. Are the surface trace lengths and widths of the major deformation zones representative at depth? The location of the major deformation zones are treated deterministically (R-07-45, §5) but involve projections from surface traces supported by single-borehole interpretations of "possible deformation zones" (R-07-45, §3.3). These assume constant length, width and planarity with depth (see Stage 2.2 Site Descriptive 3-D Model reported in R-07-45, Fig. 5-12, reproduced here in Figure 1, TOP). However, as also indicated in TR-08-05 (p. 141-142), fault zone architecture typically involves branching, undulating structures whose widths can vary significantly with depth (Figure 1, BOTTOM). This is especially relevant to the WNW-NW sets, which are reported as showing clear evidence of a combined ductile and brittle deformational history (TR-08-05, p. 170). Thus, a significant degree of uncertainty to the location and width of the major deformation zones at the repository level can be expected, which may impact the number of Deposition Tunnels/Holes available in relation to the 100 m respect distance criteria. Uncertainty is acknowledged with respect to the characteristics of the deformation zones at depth (TR-08-05, §5.9.2), however it is not evident that this is considered in the qualitative risk analysis in the underground layout design (R-08-116, §8) where increased width and/or change in position may result in altered respect distances that impact to a higher degree on the deposition area.

2. Could there be more problematic sub-horizontal faults at the repository depth than that assessed and accounted for in the Site Descriptive Model? Three gently dipping deformation zones (ZFMA2, ZFMA8 and ZFMB7) are specified as entering the target volume between 400 and 600 m depth, with two of these occurring along or close to the roof of the repository volume (TR-08-05, p. 148). These zones are reported as showing only brittle deformation and having thicknesses that range between 6 and 44 m.

Such features could act as hydraulic conduits, increase the risk of canister shearing, negate large numbers of potential Deposition Holes (based on the EPFC), as well as cause significant construction challenges. Identification of the gently dipping fracture zones is reported to be based on prominent reflectors in the seismic reflection data supported in part by the single-borehole interpretations (TR-08-05, p. 143). This raises the question as to the resolution of the geophysical methods used, as sub-horizontal deformation/fault zones less than the thicknesses reported (i.e. <6 m thick) could equally be problematic. These would also be difficult to detect through cross-correlation with the single-borehole interpretations. Data bias is reported for the north-eastern half of the regional model with respect to the absence of gently dipping zones (reflection seismic data was not available for this area; TR-08-05, p. 175). The size and variation in intensity of the gently dipping fracture zones are acknowledged as significant uncertainties in the Site Descriptive Model (TR-08-05, p. 175), however, the likelihood of encountering a sub-horizontal fracture at the repository level does not appear to be considered in the qualitative risk analysis for the underground layout design (R-08-116, §8). There may be a need to provide provision and contingency for adjusting the vertical elevation of some deposition areas if unfavourable subhorizontal zones are encountered within the horizon or near enough to critically impact deposition hole acceptance (via the EFPC).

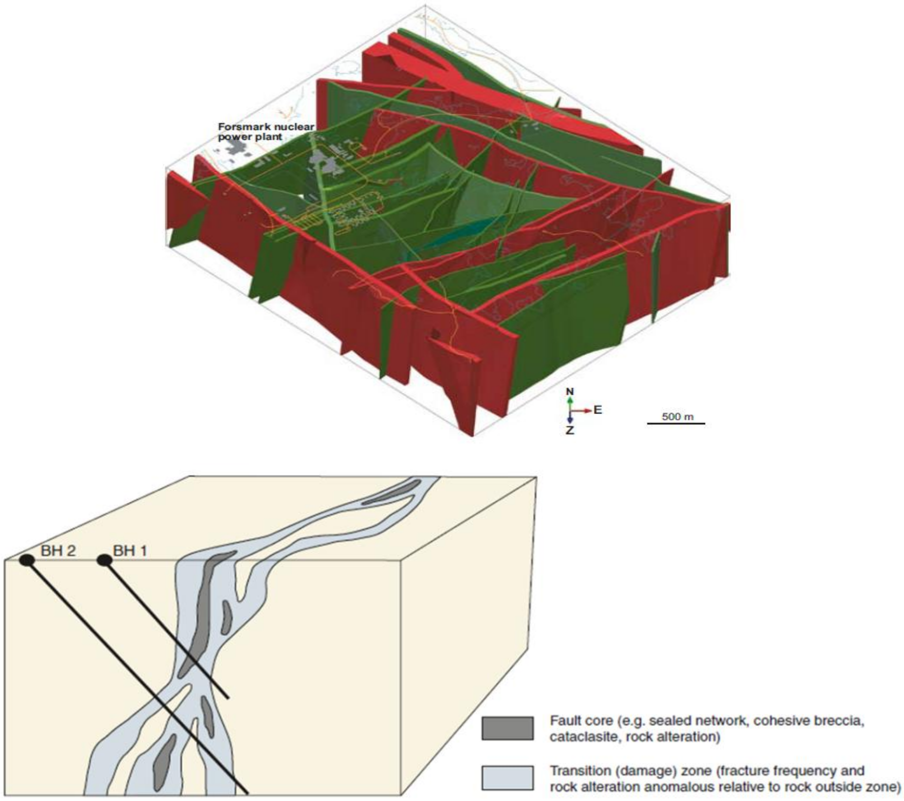


Figure 1: TOP – Steeply dipping deformation zones included in the 3-D local model, stage 2.2. Zones marked in red have a ground surface trace length > 3 km and those in green are between 1 and 3 km. BOTTOM – 3-D geometric model for a brittle deformation zone inside the north-western targeted part of the tectonic lens at Forsmark (TR-08-05, Fig. 5-26). Attention is drawn to the variable character of the zone along the two borehole intersections.

B. Review Comments Related to Constructability:

The focus of SR-Site (TR-11-01) and the Forsmark site description (TR-08-05), with respect to the site geology and its influence on the construction of the KBS-3 repository, concentrate on the two rock domains that define most of the target volume: RFM029 and RFM045. These are well-described with respect to the initial state (TR-11-01, §4) and the geometrical and mechanical characterization model (TR-08-05, §7). Less attention is given to the bounding rock domains and deformation zones, at least with respect to how they may adversely influence the local rock mass conditions and construction. Specifically:

1. RFM012 and RFM044, which are located along the west margin of the target area (Figure 2, TOP), are not discussed in TR-11-01. They are noted briefly in TR-08-05 as being domains that are affected by a high degree of ductile strain (§5.4.4, p. 136). Inspection of the geological data reported in R-07-45 suggests that these domains are associated with major tectonic features that appear to be splays of the Eckarfjärden regional deformation zone. For example, RFM012 is bound by major deformation zones (surface trace lengths >3 km; see ZFMNW1200 and ZFMWNW0123 in Figure 2, BOTTOM). It is likely that these domains will be tectonically disturbed, at least in part, and therefore will be significantly weaker than the rock encountered in RFM029 and that assumed in the various construction reports (see point 2).

2. The layout diagrams for the facility in R-08-116 show that segments of the transport tunnel along its western perimeter will be hosted in these weaker domains (Figure 2, TOP). Other segments are shown as being located along the ZFMWNW0123 major deformation zone (Figure 2, BOTTOM). R-08-116 (p. 37) cites findings in R-08-83 as showing that the rock mass quality of the deformation zones is suitable for locating either the main or transport tunnels. However, relevant sections of R-08-83 (§4.2) do not appear to consider the increased tectonic disturbance to the domains along the western perimeter. Furthermore, whereas a ground type GT4 is specified on p. 61 as applying to the major deformation zones (>3 km), the summary of expected distribution of ground types in the target volume indicates that GT4 will not be encountered (see R-08-83, p. 56). This summary does not appear to agree with the geological data, which suggests that at least some percentage of the transport tunnels will be impacted by poor rock mass conditions related to major deformation zones, specifically ZFMWNW0123 and ZFMENE0060 (Figure 2, BOTTOM).

3. The layout diagrams for the facility in R-08-116 show that the two ventilation shafts are to be located near/within areas of weaker rock and higher water inflows related to major deformation zones (>3 km). The western ventilation shaft appears to be located near a fault that offsets the two tectonically disturbed domains noted above, RFM012 and RFM044 (Figure 2, TOP). The eastern ventilation shaft appears to be located near/within ZFMENE0060 (Figure 1, BOTTOM). While there is operational and sound reasoning for positioning the shafts as proposed, it is not clear that a risk-benefit optimization analysis has been carried out to balance the construction risks associated with shaft sinking and support in these weaker zones versus the need to place the shafts away from the storage areas yet in locations that ensure proper airflow throughout the facility.

4. Note that respect distances are specified for the Deposition Tunnels relative to the major deformation zones, and design aspects related to the layout and locating of the central area likewise considers the adverse influence of the deformation zones. The questions raised here are specific to the transport tunnels and ventilation shafts.

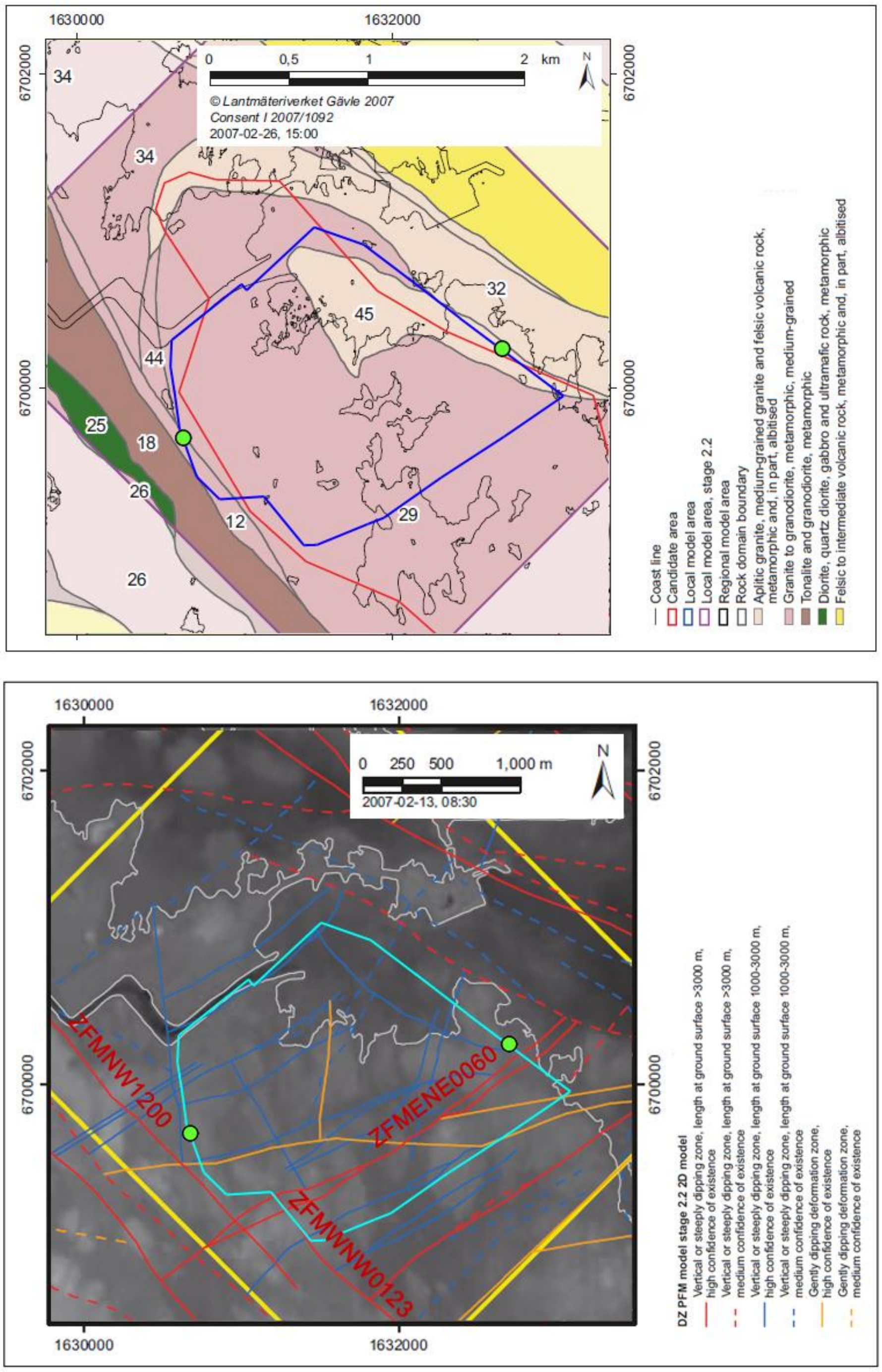


Figure 2: Planned location of the transport tunnels (blue lines) and ventilation shafts (filled green circles) from Figures 4-10 and 4-15 in R-08-116, superimposed on drawings of the rock domains (TOP) and surface intersection of deformation zones (BOTTOM). Modified from Figures 4-4 and 5-10, respectively, in R-07-45.

C. Recommendations (Category: Clarification/Submission): The assessment of likelihood of encountering sub-horizontal brittle fracture zones at the repository depth does not appear to be considered in the qualitative risk analysis. This appears to be based on the identification of only three gently dipping deformation zones in the Site Descriptive Model. Clarification is requested as to the resolution of the detection methods used (seismic reflection, single-hole interpretations) with respect to the minimum sub-horizontal deformation zone detectable.

D. Recommendations (Category: Detailed Review/Further Review): Further review may be required as to the likelihood and impact of increased width and/or change in position of the major deformation zones on the reference design and underground layout design with respect to increased impact of respect distances within and around the deposition area.

E. Recommendations (Category: Detailed Review/Further Review): Further review may be required as to whether increased tectonic disturbance and poorer rock mass conditions than accounted for can be expected along the western margin of the repository, and what impact this may have on the constructability and safety of the transport tunnels and ventilation shafts.

4.1.2. Thermal Properties and Spalling Strength

A. Review Comments Related to Design Premises:

Relevant *Design Premises* discussed in SR-Site (TR-11-01) related to the rock strength and thermal properties include:

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

The feedback to this *Design Premise* (TR-11-01, §15.5.15) suggests that even when the spatial variability of the rock thermal properties is accounted for, there is an adequate margin to the peak temperature criterion for the buffer (< 100°C). It is further suggested that careful thermal management of the disposal sequence can be used to avoid situations where a canister is deposited in a deposition area where nearby positions were deposited several years before resulting in buffer temperatures that would exceed the peak temperature criterion.

The validity of the thermal dimensioning and expected temperature distribution to which the *Design Premise* applies is outside the scope of this review. Therefore, the comments/issues discussed here only apply to the thermal properties and their determination (as used in the thermal dimensioning calculations). SR-Site reports a high degree of confidence in the modelled distribution of thermal properties (seeTR-11-01, §4.3.3), pointing to the Site Description Model (TR-08-05) for the reporting of the distribution of modelled thermal conductivities. TR-08-05 subsequently points to R-07-47 and R-08-65 for the respective modelled distribution of thermal properties for RFM029 and RFM045, respectively. Review comments and open questions related to these reports and others related to the thermal properties are:

1. Thermal conductivity is a temperature-dependent parameter. Values for the different lithologies were obtained using the Transient Plane Source (TPS) method, testing at 20, 50 and 80°C (see test procedure described in P-04-

186). A quick check of the thermal dimensioning modelling procedure (R-09-04) suggests that the temperature dependence in the thermal conductivity was accounted for. TPS values compared reasonably well to those derived using the Self Consistent Approximation (SCA) method (see R-07-47, p. 33 for comparison). Further verification of these values is likely only meaningful once it becomes possible to make *in situ* measurements. SKB subsequently acknowledges that an alternative method(s) for determining thermal conductivity *in situ* at a canister-relevant scale is required (R-11-14, p. 65).

2. Variability and heterogeneity of the thermal properties were accounted for stochastically, with distributions being derived for RFM029 and RFM045. However, several comments are made in the reporting of the derivation of these distributions that the largest uncertainty applies to the amphibolites (e.g., R-07-47, p. 6). It should also be noted that rock types involving tonalite (101051) together with diorite dykes, have low thermal conductivity values similar to the amphibolites (see R-07-47, p. 70) due to their lower quartz percentage. Rock type 101051 appears to be considered in the stochastically derived distributions of thermal properties, but the dykes are not. Thus, the thermal dimensioning does not account for localized pockets of low thermal conductivity that may be associated with dykes, dyke swarms or larger amphibolites lenses. It is not clear if this occurrence in proximity to one or more Deposition Holes should be accounted for in the exclusion criteria. TR-10-18 states as fact that Deposition Holes in rock with low thermal conductivity will not be permitted, resulting in loss of canister positions (p. 35). However, this fact does not appear in SR-Site (TR-11-01) or possibly other higher level documents.

3. The inclusion of the lower conductivity rocks in the stochastic modelling of the thermal properties assumes a certain volumetric percentage of the amphibolites (102017) and the tonalitic varieties of granodiorite to tonalite (101051). It is not clear if the subsequent thermal dimensioning accounts for variations in these percentages that may be higher. Similarly, other distinct rock types (e.g. vuggy granite associated with quartz dissolution; see R-07-45, §3.4.4) do not appear to be considered. The discussion of influence of alteration on thermal conductivity in R-07-47 (§3.3.3) does not include quartz dissolution, which given the dependence of quartz on thermal conductivity, may be of minor significance locally where quartz dissolution occurs.

<u>B. Review Comments Related to Constructability</u>:

Deformation and strength properties for the Forsmark rock types are presented in the site description report, which concludes that there is a high degree of confidence in the properties of the dominant rock types in rock domains RFM029 and RFM045 (TR-08-05, §11.2.6). Similar conclusions are made with respect to the rock mass and fracture properties (TR-08-05, §11.3.5). Remaining uncertainties are reported with respect to the uniaxial compressive strength of the subordinate rock types (amphibolites and fine-/medium-grained metagranitoid), and up-scaled properties of the fractures. Further issues raised in the review of the rock mechanics properties that may negatively impact construction include:

1. The description of the rock mass and its properties are based on statistical treatments of the data. This adds an element of uncertainty to the influence and possible adverse effects of distinct rock types and other rock mass heterogeneities.

2. The key parameter assessed with respect to spalling potential is the crack initiation stress. Crack initiation values from laboratory testing are considered to be a lower-bound approximation of the *in situ* spalling strength (TR-07-01, p. 103). This was extended to the spalling analysis reported in Appendix C of R-08-116. It should be noted though, that the laboratory procedure used to determine the crack initiation values, as described in TR-07-01 (§8.3), introduces a significant degree of subjectivity and error. The technique is based on plotting strain gauge data from uniaxial compression tests and picking the point of crack volumetric strain reversal, which is calculated from (and therefore partly dependent on) Young's modulus and Poisson's ratio values. Apart from the differences in values that may arise from uncertainties in the elastic constants, selecting the point of reversal has an approximate accuracy +/- 25% given the flatness of the minima of the curve and resolution of the stress-strain measurements (Figure 3). As acknowledged in TR-07-01 (p. 103), determination of the crack initiation stress is not straightforward. Although the uncertainty in the stress field is the dominant uncertainty with respect to spalling potential, should consideration also be given to the impacts of uncertainty in the spalling strengths on design?

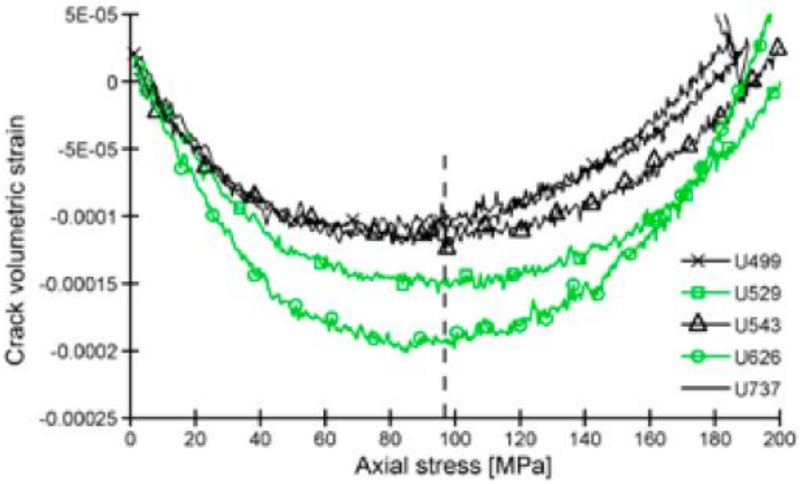


Figure 3: Uniaxial compressive test data showing selection of the crack initiation stress value (dashed line) based on the crack volumetric strain reversal. Note subjectivity (+/- 25%) in picking the point of reversal due to the flatness on the minima. From Figures 8-10 in TR-07-01.

C. Recommendations (Category: Clarification/Submission): Is the exclusion of Deposition Holes in low thermal conductivity rock included in the Deposition Hole acceptance/rejection criteria? Do the analyses of loss of Deposition Hole positions account for the likelihood of amphibolite lenses occurring more frequently than indicated?
D. Recommendations (Category: Clarification/Submission): What methodology will to be used to reliably characterise less common rock types (e.g. amphibolites lenses, vuggy granite, etc.) in near-field during construction?

E. Recommendations (Category: Detailed Review/Further Review): Further review may be required as to the spalling strengths adopted, the corresponding uncertainty, and whether this should be considered as an uncertainty/geohazard in the qualitative risk analysis of site uncertainties on design. If so, this uncertainty should be considered in tandem with the uncertainty regarding *in situ* stress.

4.1.3. Observational Method

The Observational Method is a suitable risk management technique to deal with geological uncertainty during construction. Its implementation requires several actions as outlined in TR-10-18 (§3.2) and Eurocode 7: (i) establish acceptable limits of behaviour, (ii) assess range of possible behaviour, (iii) devise monitoring plan to reveal whether the actual behaviour lies within the acceptable limits, (iv) ensure response time of instruments and data processing is sufficient to allow enough time for intervention, and (v) devise a plan of contingency actions if the monitoring reveals behaviour deviates outside acceptable limits.

A. Review Comments Related to Constructability:

The above noted requirements pose several challenges in ensuring that the fundamental requirements of stability, tightness and durability of the final repository are met. Several questions/comments can be posed with respect to the implementation of the Observational Method and relying on it to manage uncertainty related to the rock conditions to be encountered:

1. Contingency actions are required to react to unexpected or more adverse conditions than expected being encountered during construction. This is integral to the Observational Method. However, R-08-116 states that the detailed plans for contingency actions won't be developed until the next design step (p. 93). It is not clear when this next design step will be taken, but it is critical to assessing the feasibility of the repository. As noted in R-08-116 (§3.6, §8.5.2), possible actions may include the need to develop an alternative layout plan, increase the Deposition Hole spacing, etc. Thus it is conceivable that a series of adverse and unfavourable conditions are encountered that require changes to the layout that may significantly alter the number of Deposition Holes available, or significantly decrease worker safety and increase costs.

2. Several consequences in response to geohazard risk are propagated through a qualitative risk analysis of site uncertainties on the reference design (R-08-116, §8.4). However, the likelihoods of occurrences assigned appear to be weighted towards favourable acceptances of the surface and borehole investigation data as being representative of the rock conditions that will be encountered. For example, R-08-116 suggests that it is:

- Unlikely that there will be deviations from the proposed distribution of the rock types at depth (G2);
- Extremely unlikely that the frequency of long fractures will depart from the predictions of the Geo DFN Model (G3);
- Unlikely that the thickness of minor deformation zones exceeds the estimations in SDM-Site (TR-08-05) (G6);
- Unlikely that the properties of the major deformation zones deviate from the design values (R1);
- Unlikely that the orientation and magnitudes of the in-situ stresses exceed the values in the rock stress model (R2 through R4);
- Unlikely that the geometry of the thermal domains deviates from the model (T1);
- Unlikely that amphibolites and dykes occur more frequently than in the model (T2).

It is this uncertainty and the need to obtain data at depth during construction that the Observational Method is being applied. In this sense, there is a risk that the likelihoods assigned (R-08-116, §8.3) are not as conservative as reported.

3. A limitation of the Observational Method is if a ground condition is encountered for which there is no contingency action that can be feasibly implemented. What is the impact of a significant deviation from the design response in terms of construction and operation? Are there any issues that are “show stoppers” (that the Observational Method cannot fix)?

4. Several uncertainties are listed in the Site Description Model (TR-08-05) relating to the geology, thermal properties and rock mechanics state, for which the Observational Method is to be used. When will the location and width of the major deformation zones be established at the repository depth? Will invasive investigative drilling be allowed if it doesn’t align with a planned tunnel? How will the 100 m respect distance be imposed if the exact locations of the deformation zones outside the footprint of the repository aren’t known? What if a gently dipping major/minor fracture zone is encountered at the repository depth (one that may be below the detection threshold of the surface geophysics or single-hole interpretations)? What if the fracture characteristics (size/intensity) based on surface outcrop data are more favourable than those at depth? What if the distribution of rock types/thermal rock classes deviates significantly from the design values? What if the horizontal stress magnitudes are significantly higher than expected? Can the Observational Method react to these open questions in a manner that is safe and economical while still ensuring the Design Functions are met?

5. Similar to the previous comment, uncertainty in the size distribution and size-intensity model for fractures at the repository depth can only be reduced by data collected underground beneath 200 m (TR-08-05, p. 432). Uncertainties in stress magnitudes won’t be reduced until observations and measurements are made during the construction phase (TR-08-05, p. 432). Some of these uncertainties will be addressed during the early stages of construction (e.g. *in situ* stress). Others, however, may not be resolved until after construction and operations are well underway (e.g. presence of adverse geology/fractures). What are the implications if the rejection ratio of Deposition Holes doubles (triples) in the planned second half of the

repository from experiences in the first half of the repository when options for adapting are significantly more limited? Note that although it is not included in SR-Site (TR-11-01) as a *Design Premise* for long-term safety, TR-10-18 includes a *Design Premise* stating “The repository shall have sufficient capacity to store 6,000 canisters” (p. 20).

B. Recommendations (Category: Clarification/Discussion): A detailed discussion regarding plans to develop contingency actions in response to adverse ground conditions, if encountered, may be beneficial. Clarification as to how these will couple *Design Premise* requirements with worker safety and construction cost requirements should be established.

C. Recommendations (Category: Clarification/Discussion): Some of the uncertainties to be managed by the Observational Method will not be resolved until after construction and operations are well underway (e.g. presence of adverse geology/fractures in the farther reaches of the repository). What are the implications if the rejection ratio of Deposition Holes doubles (triples) in the planned second half of the repository from experiences in the first half of the repository when options for adapting are significantly more limited?

D. Recommendations (Category: Detailed Review/Further Review): Are there scenarios that the Observational Method won’t be able to react to in a manner that ensures worker safety, project economics and/or the *Design Premises* being met, and how do the options for adaptation change with different stages of repository construction and operations? Are there operational and post-closure considerations that cannot be tested through the Observational method?

E. Recommendations (Category: Detailed Review/Independent Analysis): An independent assessment of the geohazard risks and their likelihood of occurrence may be required. This should maybe include an independent analysis of Deposition Hole rejection scenarios relative to one or more geohazard risks being realized.

4.2. *In Situ* Stress State

The initial state of stress at the repository level, and its profile from surface, have been proposed based on a combination of *in situ* stress measurements at depth, a consideration of the tectonic regime and trends, as well as from back analyses of borehole performance (breakouts). This analysis is detailed in R-07-26, R-07-31 and P-07-206, and the results are summarized in R-08-116 (p. 27) reporting the most likely, unlikely minimum and unlikely maximum stress magnitudes and their orientation.

While there is no specific *Design Premise* directly related to the *in situ* stress state, the initial stress state represents a key boundary condition and input that impacts the degree of spalling in both the Deposition Tunnels and Holes as well as structural stability (fallout from roof and shear in floor). It is also a controlling factor for shaft constructability and rock reinforcement, as well as the coupled hydro-mechanical behaviour of the fracture systems.

The working ranges for *in situ* stress for design purposes are reproduced in Table 2 from R-08-116 (§3.4).

Table 2: Stress magnitudes and stress orientations for the three stress models (most likely, unlikely minimum and unlikely maximum) used for Design Step D2. From R-08-116 (§3.4).

Depth Range (m)	Maximum horizontal stress – σ_H (MPa)	Trend (°)	Minimum horizontal stress – σ_h (MPa)	Trend (°)	Vertical stress – σ_{vert} (MPa)
Most Likely					
0–150	**19+0.008z, ±20%**	145 ±20	11+0.006z, ±25%	055	0.0265z ±0.0005
150–400	9.1+0.074z, ±15%	145 ±15	6.8+0.034z, ±25%	055	0.0265z ±0.0005
400–600	29.5+0.023z, ±15%	145 ±15	9.2+0.028z, ±20%	055	0.0265z ±0.0005
400	38.7 ±5.8	145 ±15	20.4 ±4.0	055	10.6 ±0.2
500	41.0 ±6.2	145 ±15	23.2 ±4.6	055	13.2 ±0.3
Unlikely minimum scenario					
400	19.2 ±0.7	124 ±6	9.3 ±1.1	034	10.4
500	22.7 ±1.1	124 ±6	10.2 ±1.6	034	13.0
Unlikely maximum scenario					
450–475	56 ± 6	145 ±15	35 ±15	055	0.0265z ±0.0005

A. Review Comments Related to Constructability:

Questions/comments arising from our review with respect to the initial stress state reported and its determination include:

1. Stresses have been measured at a variety of locations within or near the target area, and directly related to the repository volume. A number of these measurements (in particular those from KFK001/DBT1) have been discarded in the final interpretation process. This filtering of data is justified in R-07-26 based on a number of arguments including the comparison with other indirect stress estimation techniques such as back analysis of borehole breakout data (§8). As stated in the Site Description report (TR-08-05, p. 215):

   "*It should be noted that the deepest overcoring measurements from KFK001 (DBT1) are questionable. The reasons for this are described and discussed in detail in /Martin 2007/, where also established trends in the data sets are presented, expressed as, for example, the mean stress and the ratios between the principal stresses.*"

   Removal of this borehole from the dataset results in a significant change in the interpretation (see Figure 4). Rejection of this data needs to be more thoroughly justified and seems to be based on the overestimate of vertical stress. While this does justify possible rejection of the data, it is possible that this overestimation of vertical stress (higher than overburden pressure) is due to anisotropic damage in the vertical core resulting in a higher vertical stress estimate (i.e., greater relaxation strains in the overcore in this direction). Such damage would not have the same impact on the horizontal stress estimates. Similarly, there are numerous uncertainties in the alternative approaches (including estimate of true borehole strength for back analysis of breakouts) that it is unclear as to the justification for exclusion of some of the overcoring data. As such, the *in situ* stress values are based on a number of unverified (although possibly valid) assumptions, under which the stated "likely" maximum stress (σ_H) at the target depth could be underestimated by up to 25 to 35% (i.e., resulting in "likely" horizontal stresses as high as 50-55 MPa instead of the stated 41 MPa). While this higher range is reported, it is taken into account as an unlikely scenario. Note that the implication of higher stresses or more extreme stress ratios is the inclusion of spalling and/or structural shear. These mechanics do not currently figure in the design considerations.

2. What is the mechanism by which the trend of the maximum horizontal stress decreases in gradient at 400 m depth but the trend of the minimum horizontal stress remains linear (see red dashed box in Figure 4). The change in trend at 150 m makes sense as a different fracture domain is being entered (and is reflected in both the maximum and minimum horizontal stress). However, there is very limited justification for the decrease in trend at 400 m in the reports provided. The conclusion is discussed in R-07-26 (§7.2.4) although the reasoning is potentially insufficient to justify such a significant diversion from the measured trends.

3. It is unclear whether the stress regime measured in boreholes KFK001/DBT1 and KFK003/DBT3 are applicable to the repository volume. The Site Description report (TR-08-05) reports these boreholes as being drilled in FFM04 (p. 214), which is situated outside the target volume and involves different rock and fracture domains (see Figure 5). Given the complex regional structural geology, and the influence it can have on the stress field (as seen in the change in trend at 150 m in Figure 4), the applicability of these measurements to the repository volume is questionable. As shown in Figure 4, these data points represent the majority of the data on which the *in situ* stress interpretation is based.

4. Is there an issue with the early use of the Borre probe, which was subsequently revised/improved for subsequent measurements? This again applies to the compatibility and reliability of the stress measurement data from KFK001/DBT1 and KFK003/DBT3, which were made using an early prototype of the Borre probe (R-07-26, p. 45).

5. It is unclear how the measurements of Ask et al. (P-07-206) were considered in the final determination of the stress gradient. These were hydrofracture measurements.

6. The final determination of *in situ* stress is the result of a number of assumptions, simulations, and filtration of (possibly incompatible) measurements. This process must be better summarized in the final documentation with associated justifications clearly and briefly explained, as it is critical to the assignment (and verification) of the “likely” and maximum/minimum “unlikely” scenarios (e.g., as used in the qualitative risk assessment and assessment of potential loss of deposition-hole positions due to spalling reported in R-08-116).

<u>B. Recommendations (Category: Clarification/Submission)</u>: Clarification is requested as to the mechanism by which the trend of the maximum horizontal stress is interpreted to decrease in gradient at 400 m depth but the trend of the minimum horizontal stress remains linear.

<u>C. Recommendations (Category: Clarification/Submission)</u>: Are the stresses measured in boreholes KFK001/DBT1 and KFK003/DBT3 located outside the target volume and in FFM04 applicable to the repository volume? How would the stress interpretation change if these data were excluded?

D. Recommendations (Category: Clarification/Discussion): A single unified summary of the combined set of measurements, analyses and assumptions (including filtering logic) for the determination of the *in situ* stress regime (trends and ranges) needs to be compiled. The current documentation is complex and leads to the risk of overly confident stress specifications.

E. Recommendations (Category: Clarification/Discussion): A discussion would be beneficial regarding the selection of the representative *in situ* stress and associated ranges (likelihoods) at the repository horizon, as well as provisions for follow-up refinement and implications for design of realistic deviations from this base case (both deviations from the average predicted stress field and local stress anomalies).

F. Recommendations (Category: Detailed Review/Further Review): Further review may be required for the currently adopted stress regime at the repository location, including the impact of realistic deviations from this assumption coupled with the uncertainties in strength and stiffness (including local geological heterogeneities).

G. Recommendations (Category: Detailed Review/Independent Analysis): An analysis of cumulative error propagation is required tracing assumptions and uncertainties in defined stress regime through EDZ assessment and support calculations.

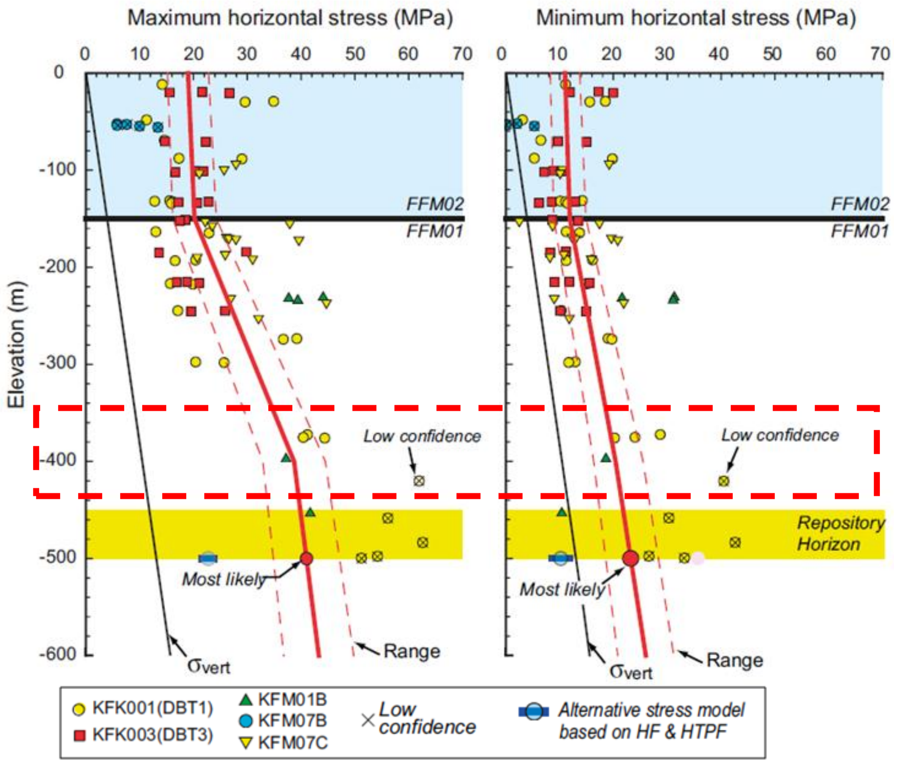


Figure 4: Evaluated *in situ* stress state at Forsmark, from Figure 7-18 in TR-08-05. Red dashed box added to highlight depth at which the maximum horizontal stress trend decreases in gradient without a corresponding change in trend for the minimum horizontal stress. Measurements marked as low confidence (with an X) are overcoring results from KFK001/DBT1.

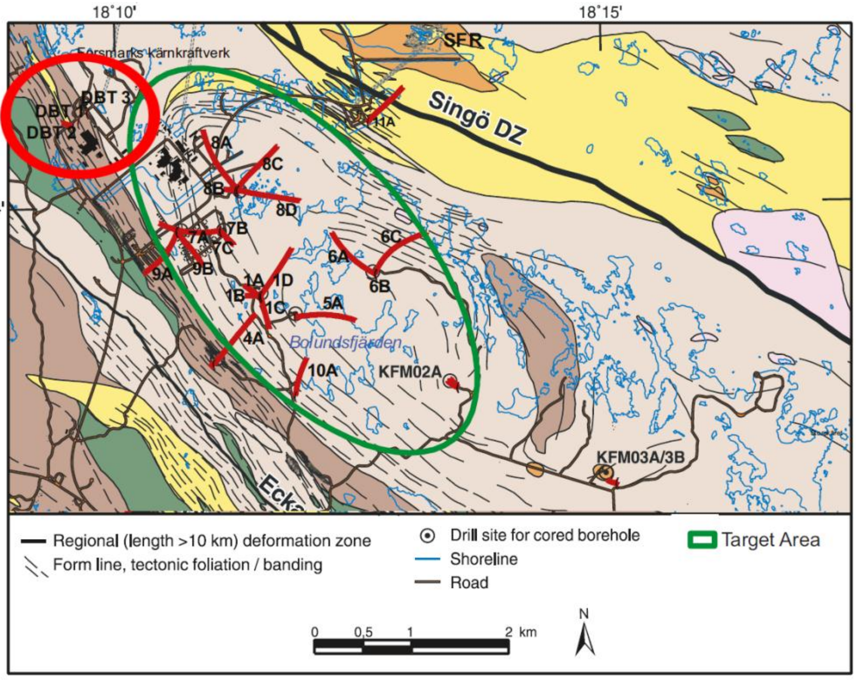


Figure 5: Map of the Forsmark site showing the locations of the cored boreholes, from Figure 2-10 in R-07-26. Red circle added to highlight locations of DBT1 and DBT3 (stress measurement boreholes) outside the Target Area.

4.3. Excavation-Induced Damage and Spalling

Note that thermal-induced spalling was explicitly not included as part of this review assignment.

<u>A. Review Comments Related to Design Premises:</u>

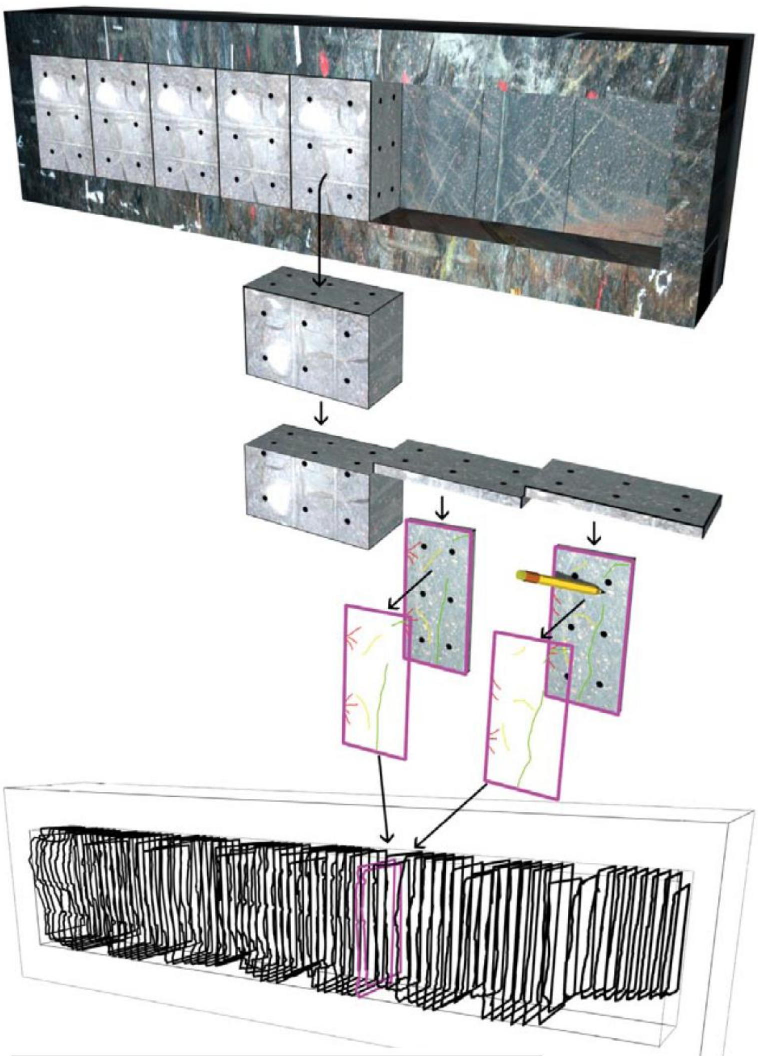
Relevant *Design Premises* discussed in SR-Site (TR-11-01) related to excavation-induced damage and spalling include:

- *Excavation induced damage should not result in a connected effective transmissivity, along a significant part of the disposal tunnel and averaged across the floor, higher than 10^{-8} m^2/s.*

SR-Site (TR-11-01) takes the position that there is ample evidence suggesting that any potential EDZ formed during excavation will be kept below the maximum allowed transmissivity. Furthermore, they point to the same evidence as suggesting that any EDZ that forms will not be continuous (§15.5.16). Issues/comments raised in our review with respect to EDZ and spalling include:

1. The conclusion that the EDZ if it develops is not continuous is based on the conclusions from a large *in situ* experiment conducted at Äspö, as reported in R-09-39. This experiment was conducted under a stated *in situ* stress field with σ_1 = 25-35 MPa, oriented at 30 degrees from horizontal. A tunnel was excavated using drill and blast techniques, from which samples were cut from the tunnel wall (Figure 6). First, it should be noted here that these test conditions are based on lower stress conditions than those expected at Forsmark. More importantly though, the samples were cut from the tunnel

walls and not the tunnel roof. Such samples will capture the blast-induced damage, which would be expected to develop more or less uniformly around the entire tunnel perimeter. However, any fracture damage resulting from the redistribution of stresses (i.e. stress-induced damage) would be expected to concentrate in the tunnel roof and floor in response to the stress field orientation. As such, any conclusions derived from this study can only be extended to the connectivity of blast induced damage (i.e., Construction Damage Zone, CDZ) and not the stress-induced EDZ. Given that blast fractures would be expected to be radial relative to the tunnel boundary, it is not surprising that subsequent testing of the rock showed that the damage was not connected along the length of the tunnel.



	σ_1	σ_2	σ_3
Magnitude [MPa]	25–35	15	10
Trend (Äspö96)	310	090	208
Plunge (degrees from horizontal)	30	53	20

Figure 6: EDZ experiment at Äspö, showing block extraction from tunnel wall to analyze for continuous EDZ. Superimposed are the stated stress magnitudes and orientations for the experiment location. From Figure 4-6 and Table 2-1 in R-09-39.

2. Blast damage related to construction (CDZ) should be considered separately from EDZ, which results from stress redistribution subsequent to excavation. CDZ can be reduced using smooth-wall blasting techniques, as concluded in TR-10-18 (p. 45), where it is proposed as a means to control and prevent continuous EDZ from developing. However, this does not apply to stress-induced EDZ. CDZ and EDZ should be treated as separate considerations.

3. Should there be acceptance criteria restrictions related to amphibolite lenses, mafic dykes and foliation/banding due to increased spalling potential? Similarly, adverse fractures are accounted for in the EFPC but what about excess (continuous) EDZ or possibly, the development of an excavation fracture zone (EFZ) involving spalling, interconnected fractures, increased apertures, extensive slip/opening of existing fractures, etc.? Should fractures that meet only part of the EFPC criteria, therefore resulting in an acceptable Deposition Hole, be re-evaluated if they intersect a continuous EDZ/EFZ in the Deposition Tunnel floor? Should a continuous EDZ/EFZ be included as part of the EFPC?

4. In addition to spalling, excavation-induced stresses can also result in fracture reactivation or coalescence between non-persistent fractures, which may be mapped initially as acceptable with respect to the EFPC but subsequently exceed it. Respect distances and EFPC criteria only allow for fracture persistence/extent as mapped, not for the possibility that fractures may propagate/coalesce as stresses change with continued construction of the repository and increasing rock temperatures, thereby resulting in longer, more continuous fractures.

5. Although thermal-induced spalling was not part of our review assignment, it is noted here that uncertainties in stress, spalling strength, thermal conductivity and coefficient of thermal expansion may combine to create a likelihood of thermal spalling. SR-Site states that the counter pressure exerted by bentonite pellets in the slot between the buffer and rock wall may suppress the spalling, or at least keep the spalled slabs in place and minimise the hydraulic transmissivity of the spalled damage zone. However, this is only likely if the bentonite is swelling (i.e. confinement from swelling pressures may work to suppress thermal spalling). If the bentonite is still dry, the counteracting pressures due to the self weight of the pellets (depending on their packing density) will likely be insufficient.

6. Although the topic of time-dependent behaviour and long-term evolution of stress-induced brittle fractures applies more to the timeframe of the operation and closure phases of the repository, and therefore is not addressed here in detail. It should be noted that the topic is one that is generally not well understood. Concepts such as sub-critical crack propagation and stress corrosion in response to environmental changes (temperature, humidity, chemical interactions) have been proposed to suggest that stress-induced fractures in the EDZ may continue to develop and grow over time. Experimental studies examining the long-term strength and performance of crystalline rock under sustained compressive loading are limited, but suggest values that are less than 60% of their uniaxial compressive strength.

B. Review Comments Related to Constructability:

Questions/comments arising with respect to EDZ and spalling and their effect on constructability are:

1. What are the contingency plans in the event of significant overbreak owing to spalling or a roof fall along adverse dipping joints? R-05-71 indicates a possibility, albeit low, of small wedge failures for the planned Deposition Tunnel alignment (p. 37).

C. Recommendations (Gaps/Omission): There does not appear to be a Deposition Hole rejection criterion that considers a non-persistent fracture intersecting a Deposition Hole that connects with a continuous EDZ/spalling along the floor of a Deposition Tunnel (or vice versa). Continuous EDZ should be treated jointly with the fracture intersection scenarios described in the EFPC. Similarly, the EFPC criteria only allows for fracture extent as mapped, not for the possibility that the fracture may propagate/coalesce during subsequent construction/operation activities in response to further stress changes and increasing rock temperatures.

D. Recommendations (Category: Clarification/Submission): Clarification is requested with respect to the conclusion that EDZ, if it develops, will not be continuous. Is the Äspö experiment on which this conclusion is based only applicable to blast-induced damage and not excavation-induced damage resulting from the redistribution of stress and stress concentrations?

E. Recommendations (Category: Clarification/Discussion): The distinction and separation of construction damage (CDZ) from stress-induced excavation damage (EDZ) should be discussed, especially with respect to the mitigation and management measures proposed (smooth wall blasting). Also to be considered is the excavation fracture zone (EFZ), also referred to as the highly damaged zone (HDZ).

F. Recommendations (Category: Detailed Review/Independent Analysis): Uncertainties in stress and spalling strength may combine to create a likelihood of stress-induced spalling. Quick scoping calculations within the ranges of uncertainties suggest spalling could be significant. This similarly extends to the uncertainties in thermal conductivity and coefficient of thermal expansion, which likewise may combine to increase the extent of thermal spalling.

G. Recommendations (Category: Detailed Review/Independent Analysis): There is limited experience, both experimental and applied, with respect to time-dependent behaviour and long-term evolution of stress-induced brittle fractures. A more detailed and thorough review of the applicability of concepts relating to sub-critical crack propagation, stress corrosion and long-term strength degradation and performance of crystalline rock under sustained compressive loading on stress-induced fractures in the EDZ is suggested.

4.4. Layout, Excavation Techniques and Construction Sequencing

A. Review Comments Related to Design Premises:

Relevant *Design Premises* discussed in SR-Site (TR-11-01) and TR-10-18 related to layout, excavation techniques and construction sequencing include several pertaining to the buffer and backfill installation:

Buffer

- *The buffer dimensions used as reference dimensions in SR-Can shall be used, in addition to other requirements affecting the buffer and Deposition Hole geometry (TR-11-01,* §*15.5.8).*
- *Nominal thickness of the buffer around, below and above the canister (0.35 m; 0.5 m and 1.5 m). From the height of the buffer block on top of the canister to the bottom of the Deposition Hole the radius from a vertical line in the centre of the Deposition Hole shall be at least 0.84 m. From the height of the buffer block on top of the canister to the bottom of the Deposition Hole the radius from a vertical line in the centre of the Deposition Hole must not exceed 0.925 m.(TR-10-18, §2.3.2).*

Backfill

- *Packing and density of the backfill, both at initial dry state and after complete water saturation, must be sufficient to ensure a compressibility that results in a minimum buffer saturated density according to the conditions set out (i.e. 1,950 kg/m^3) with sufficient margin to loss of backfill and to uncertainties (TR-11-01,* §*15.5.11).*
- *For each blast round the total volume between the rock wall contour and the nominal contour of the Deposition Tunnel shall be less than 30% of the nominal tunnel volume. The maximum cross section shall be less than 35% larger than the nominal cross section. To achieve a dependable backfill installation the tunnel floor must be even enough for the backfill installation equipment to drive on it. Underbreak is not accepted. (TR-10-18, §2.3.2).*

The geometrical requirements in TR-10-18 (§2.3.2) are specified to ensure proper installation of the buffer and backfill to specification, and to ensure the minimum buffer/backfill density is maintained. The tolerances applied to the buffer are also deemed necessary to protect against buffer erosion. Considering that most barrier components are industrially produced, the feedback to these *Design Premises* recommends reformulating the tolerances in a way that provides better guidance to designers, for example by reformulating them into minimum dimensions and maximum gaps allowed (TR-11-01, p. 825). Related review comments/open questions raised here include:

1. In the description of the repository layout and Linear Development Method, no discussion is provided with respect to the influence of the excavation sequencing on the development of stresses around/between the Deposition Tunnels and boreholes as the repository is constructed. No original source or explanation was found for the 40 m centre-to-centre separation distance between Deposition Tunnels, but its use could be traced to early thermal dimensioning calculations where it was simply stated to be a reference spacing (TR-03-09; p. 74). Stress analyses performed in R-08-115 examined the tunnel profile shape, but not the 3-D stress distribution

between tunnels or the stresses that develop between later Deposition Tunnels after a significant portion of the repository has already been constructed (and the stress field significantly disturbed). In cases where higher stresses around the Deposition Holes may have developed, subsequent stresses generated by a neighbouring tunnel under construction may result in Deposition Hole displacements and possibly spalling that in turn may cause the bentonite buffer blocks to shift prior to canister placement.

2. In the Linear Development Method sequence, a separation distance of 80 m between endpoints of Deposition Tunnels located in different main tunnels is used as a safety distance for the vibrations from blasting works in relation to a deposited canister (R-08-113, p. 42). Similarly, a security zone spanning two tunnels is used to separate the nearest Deposition Tunnels undergoing construction from those in which deposition work is being undertaken (R-08-113, p. 53). However, no reference is made to the effects of heavy vehicles in the main tunnels moving back and forth, hauling waste rock or carrying heavy canisters along uneven surfaces, as a source of vibration that may cause damage to the bentonite buffer blocks before canister placement.

   Look-outs created through drill and blast advance may inhibit proper backfill expansion (Figure 7). Similar compatibility issues between the backfill/tunnel interface may also arise where blocky rock mass conditions are encountered (Figure 8). An overbreak limit of 30-35% as stated in the *Design Premise* for Deposition Tunnels seems excessive and incompatible with the requirement to minimize construction damage. If the specified total volume and section area overbreak limits are maintained, then the reviewers recommend adding a third linear limit to ensure local exceedance is minimized. For example: *Acceptable largest linear overbreak (measured normal to design profile) should not exceed the nominal 0.25×Radius for a circular profile or 0.13×Span for a square profile (see Figure 7).*

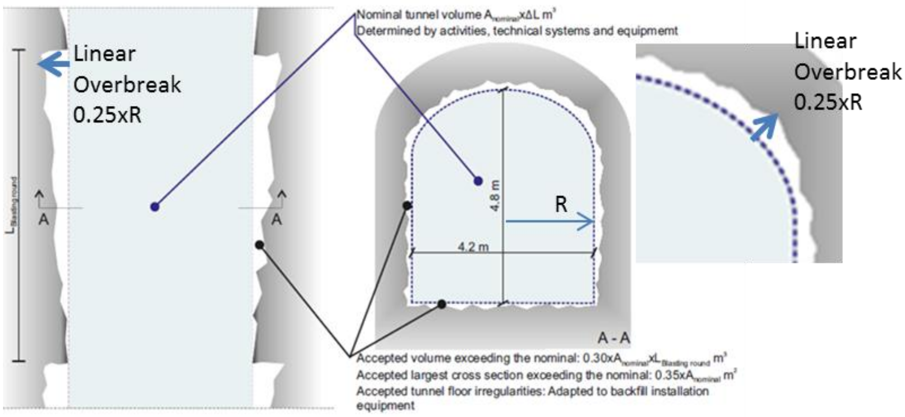


Figure 7: Irregular tunnel boundaries with look-outs created by drill and blast advance (TR-10-18, p. 24). Included is an example of a suggested linear overbreak criterion to compliment those based on total volume and section area overbreak limits.

GSI = 80–90	*RMR* = 80–90	Q = 40–100

Figure 8: Example of irregular tunnel boundary observed in a drill-and blast tunnel in a blocky rock mass (R-08-83, p. 59).

B. Review Comments Related to Constructability:

Questions/comments arising with respect to layout, excavation techniques and construction sequencing are:

1. Construction of the shafts and access ramp will require excavating through fracture domain FFM02, which involves gentle dipping and stress release fractures that are likely highly transmissive and water bearing. R-08-116 notes that the expected inflows into the various excavations will exceed the 10 ℓ/min per 100 m length set for the shafts and ramp (R-07-33, p. 51). A pilot grouting programme is planned to establish the groutability of the gently dipping fractures, with the assumption that pre-grouting ahead of the tunnel face or via a grout curtain from surface will allow the inflow criterion to be met (R-08-116, p. 68). The construction plan proceeds with the assumption that pre-grouting will be possible, and effective, but noting that schedule delays of 1-2 years may be involved due to increased grouting demands to reach acceptable levels of inflow (R-08-116, p. 89). Similar requirements will be necessary for the skip shaft and ventilation shafts, the latter being excavated by raisebore. This will require the pregrouting to extend from surface to the repository depth. A drilling deviation of 1% is specified for these holes (R-08-116, p.69), which may be challenging for the ventilation shafts given their proximity to major deformation zones (see Figure 2, BOTTOM). The skip shaft is to be excavated conventionally by drill and blast, allowing for pre-grouting to be carried out in stages as the shaft bottom advances.

2. According to the Linear-Development Method outlined in the D2 Layout and Construction Plan (R-08-113), air flow is meant to pass openly from one area to the next through the dividing wall. R-08-116 states that it is presumed that radioactivity will not influence the ventilation system (p. 52), and that no ducts for pressurized air are assumed to be necessary along the main and transport tunnels (p. 53). Nevertheless, is it deemed safe (in event of accident) to have the ventilation passing from the deposition areas

into the excavation areas as required by the Linear Development Method sequencing? It is noted in R-08-113 that fire, escape routes and other security issues need to be resolved (p. 30).

3. Vague reference is made to the possible involvement of a TBM (tunnel boring machine) in the excavation work (e.g., R-08-113, p. 22, but also several other reports). This may be a misuse of the acronym ‘TBM’, referring to the mechanized boring of the Deposition Holes as opposed to the mechanized boring of the tunnels. No TBM launch chamber is included in the layout, and a TBM for tunnel construction might only be feasible for the transport tunnel ring, but would require a modification to its layout to suit the turning radius possible with a TBM. Again, it is assumed that this is a misuse of the acronym.

4. R-08-113 also provides an estimate of 90 weeks for the total time to excavate one Deposition Tunnel (R-08-113, p. 22). With more than 200 Deposition Tunnels in the total layout plan, this will require the simultaneous excavation of several Deposition Tunnels. The use of the main tunnel and skip shaft for waste rock removal will have to be tightly coordinated. Similarly, it is stated in R-08-116 that the transport- and main tunnels will likely be constructed by external construction companies, while the Deposition Tunnels will mainly be constructed by SKB employed personnel. This will add an extra degree of complexity to the scheduling and construction as the two separate operations will be competing for the same access to the main tunnel and skip shaft for waste rock removal.

5. Construction contracts must include the requirement for an optimized unimpeded geotechnical assessment window within the construction cycle and that the geotechnical data collected during construction be of adequate quality and quantity.

6. According to the development plan, the farthest reach of the repository, Area D, will not be penetrated by the development headings until after 20 years of construction. How does this impact the overall risk of ensuring the availability of a minimum of 6,000 Deposition Holes, if the geological conditions encountered south of the major deformation zone ENE0060A are more adverse than those expected based on surface geophysics and the small number of single-hole interpretation boreholes?

C. Recommendations (Category: Gaps/Omission): It does not appear that a project cost-schedule risk assessment has been carried out with respect to construction. A qualitative risk assessment is reported with respect to geohazards, however, schedule delays and cost overruns should also be considered.

D. Recommendations (Category: Clarification/Submission): Clarification is requested as to the source and basis for the 40 m centre-to-centre separation distance between Deposition Tunnels. This appears to be based on thermal dimensioning. Have stress analyses been performed that consider the influence of excavation sequencing on the development of stresses around/between the Deposition Tunnels and boreholes as the repository is constructed? The analyses reported appear to be based on the stresses between multiple Deposition Holes in a single Deposition Tunnel.

E. Recommendations (Category: Clarification/Submission): Is the 30-35% overbreak limit expressed in the *Design Premises* for Deposition Tunnels excessive or incompatible with the requirement to minimize construction damage? Can this be reduced to improve overall quality control? If the specified total volume and section area overbreak limits are maintained, should a third linear limit be added to ensure local exceedance is minimized? For example: "Acceptable largest linear overbreak (measured normal to design profile) should not exceed the nominal 0.25×Radius for a circular profile or 0.13×Span for a square profile".

F. Recommendations (Category: Clarification/Submission): The potential for adverse effects from blasting on the deposition works are accounted for in the repository layout by imposing separation and safety distances. Are similar considerations required for other vibration sources, for example heavy vehicles carrying heavy canisters or hauling waste rock along uneven surfaces?

G. Recommendations (Category: Clarification/Submission): Clarification is requested as to the risk associated with having the ventilation passing from the deposition areas into the excavation areas, as required by the Linear Development Method sequencing, in the event of an accident involving a canister. Is this a potential issue identified in the risk assessment of worker safety or in the development of safety protocols?

H. Recommendations (Category: Clarification/Submission): Clarification is requested as to references in the different construction plan reports to the use of a "TBM". Is this in reference to a tunnel boring machine?

I. Recommendations (Category: Detailed Review/Further Review): Further review may be required as to how the construction sequence factors into the geohazard risk analysis. The farther extents of the repository will not be penetrated by excavation workings until after 20 years of construction. How does this impact the overall risk of ensuring the availability of the required Deposition Holes, if the geological conditions encountered are more adverse than expected? For example, would the construction of the Main Tunnels, Transport Tunnels and Short-cut Tunnels before proceeding to the construction of the Deposition Areas be a feasible measure to reduce uncertainties and confirm the design assumptions?

4.5. Constructability of the Deposition Holes

4.5.1. Geometrical Tolerances

A. Review Comments Related to Design Premises:

Relevant *Design Premises* discussed in SR-Site (TR-11-01) and TR-10-18 related to layout, excavation techniques and construction sequencing include several pertaining to the buffer and backfill installation:

Deposition Hole Tolerances

- *The maximum horizontal cross section area must not exceed the nominal by more than 7%, the diameter shall be at least 1.745 m (nominal diameter=1.75 m); from the height of the buffer block on top of the canister to the bottom of the Deposition Hole the radius from the vertical centre line shall be at least 0.84 m and must not exceed 0.925 m (TR-10-18, §2.3.2).*

Buffer Thickness Tolerances

- *The buffer dimensions used as reference dimensions in SR-Can shall be used, in addition to other requirements affecting the buffer and Deposition Hole geometry (TR-11-01, §15.5.8).*
- *Nominal thickness of the buffer around, below and above the canister (0.35 m; 0.5 m and 1.5 m). From the height of the buffer block on top of the canister to the bottom of the Deposition Hole the radius from a vertical line in the centre of the Deposition Hole shall be at least 0.84 m. From the height of the buffer block on top of the canister to the bottom of the Deposition Hole the radius from a vertical line in the centre of the Deposition Hole must not exceed 0.925 m.(TR-10-18, §2.3.2).*

The geometrical requirements specified in TR-10-18 (§2.3.2) are to ensure dependable installation of the buffer according to specification. The stated tolerances are to protect against all possible deviations, including alignment, straightness, displacements and rock fall out (TR-10-18, p.22). The stack of bentonite blocks is positioned so that its centreline aligns with the vertical line of the Deposition Hole. Related review comments/open questions raised here include:

1. The tight tolerances specified imply that the geometry of the Deposition Holes and stacking of the bentonite blocks are critical to the long term safety performance of the repository. If so, then the tolerances should be reformulated in a way that would allow them to be measured and verified during construction. For example, once a fuel canister is being guided into the hole, would it still be possible to detect if the canister damages the buffer on the way down or if a bentonite block is knocked out of position? What is the contingency plan if it is established that the bentonite buffer was critically damaged by the canister? Would the canister be removed so that the buffer could be repaired/replaced?

2. Will the verticality of the Deposition Hole be maintainable during drilling if a weaker amphibolite lense is intersected? Weaker rock intervals may redirect the drill head, as well as result in larger, asymmetric deformations (challenging the minimum diameter requirement), or conversely, significant overbreak. Amphibolite lenses are not covered by the EFPC (TR-10-21).

3. Note that in R-08-116, reference to overbreak >5 cm in the Deposition Holes is referred to as both requiring backfilling with bentonite pellets (p. 85) and as a Deposition Hole rejection scenario (p. 86).

B. Review Comments Related to Constructability:

The tight tolerances specified will result in significant risk with respect to constructability. Questions/comments arising from these tolerances were:

1. From a constructability point of view, sliding a 4.8 m high copper canister into a hole formed by a set of stacked, prefabricated, ring-shaped buffer blocks with only 10 mm of clearance either side (20 mm total; based on dimensions given in TR-10-14 and TR-10-15) without damaging the blocks will be challenging! The restriction on the use of shotcrete (and presumably concrete) in the Deposition Tunnels means that this operation will likely be conducted from an uneven surface.

2. Consideration should be given as to whether construction vibration from nearby activities will cause buffer blocks to shift (e.g., blasting, movement of heavy vehicles on rough, non-paved roads, etc.).

C. Recommendations (Category: Gaps/Omission): A fully demonstrated testing of the loading of the canisters at full weight and for the buffer geometry/tolerances specified would be required as a proof of concept with respect to constructability. Repeatability of the procedure should be included to determine the percentage of successful completions per attempt.

D. Recommendations (Category: Clarification/Submission): Clarification is requested as to the strictness of the Deposition Hole and buffer installation tolerances. How critical are they to the safety case? Can they be modified to allow for slightly greater tolerances in order to improve the success rate of installation? If critical, would it be better to install the canister and buffer blocks together as an integrated package allowing the integrity of the full engineered barrier to be verified before installation in the Deposition Holes?

E. Recommendations (Category: Clarification/Submission): Is there a limit on the amount of overbreak that occurs in the Deposition Holes? Should overbreak be included in the Deposition Hole acceptance/rejection criteria?

4.5.2. Bottom Hole Plate

A. Review Comments Related to Design Premises:

Relevant *Design Premises* discussed in TR-10-18 (§2.3.2) related to the Deposition Hole bottom plate are:

- *The inclination over the part of the cross-section where the bottom buffer block is placed shall be less than 1/1750.*

It should be noted that this is not included as a *Design Premise* in SR-Site (TR-11-01), but feedback on its adequacy is included since the plate is part of the reference design (p. 826). It is concluded in this feedback that its presence does not affect risk, but that given question marks surrounding its implementation, that alternative solutions be sought to provide a flat Deposition Hole bottom on which the bentonite buffer blocks can be positioned. Issues/comments related to its use in the reference design include:

1. The presence of the bottom plate is considered as an unnecessary disturbance (TR-11-01, p. 826). Ideally, the canister should be in direct contact with the bentonite buffer in the Deposition Hole. Several unresolved uncertainties stated in SR-Site include the thickness and compressibility of the plate, the possibility for a lifting of the buffer/canister package before the backfill is placed, the potential for a loss of buffer density in the bottom of the Deposition Hole, the impact inflowing water may have before deposition and the chemical interaction between the bottom plate and buffer (TR-11-01, p. 826).

2. Possible alternatives to the bottom plate may be the use of physical grinding, precision high pressure jetting, or heating/flaming finishing as used in the quarry and granite countertop industries.

3. Would installing the canister and buffer blocks together as an integrated package negate the need for the bottom plate? This would provide the added benefit of enabling testing and verification of the integrity of the full engineered barrier before it is installed in the Deposition Holes. Risk of damage to the engineered barrier would still be present, but presumably this would be highest for the interface between the rock and buffer as opposed to the interface between the buffer and canister (as is the case for the current reference design). Which interface is more critical to the safety case?

4. Horizontal deposition would negate the need for the bottom hole plate installation. However, such a major design change would need to be weighed against the adverse consequences that horizontal deposition may have on other aspects of repository construction and production, installation and performance of the engineered barriers.

B. Recommendations (Category: Clarification/Discussion): Would installing the canister and buffer blocks together as an integrated package negate the need for the bottom plate? A discussion would be beneficial regarding the sensitivities of the rock/buffer and buffer/canister interfaces with respect to the *Design Premises* and *Safety Functions*.

4.6. Grouting

A. Review Comments Related to Design Premises:

Relevant *Design Premises* discussed in SR-Site (TR-11-01) related to grouting are:

- *The total volume of water flowing into a Deposition Hole, for the time between when the buffer is exposed to inflowing water and saturation, should be limited to ensure that no more than 100 kg of the initially deposited buffer material is lost due to piping/erosion. This implies, according to the present knowledge, that this total volume of water flowing into an accepted Deposition Hole must be less than 150 m^3.*
- *Fractures intersecting the Deposition Holes should have sufficiently low connected transmissivity.*
- *Only "low pH" materials (pH < 11) are to be applied in the Deposition Tunnels.*
- *Continuous grouting boreholes outside the tunnel perimeter should be avoided.*

The feedback to these *Design Premises* suggests that the limits for water entering the Deposition Holes be changed to a more practical acceptance criterion, in which with Deposition Holes with high Darcy Flux being avoided (TR-11-01, §15.5.13). A suggested threshold of 0.1 ℓ/min being produced by a transmissive fracture intersecting the Deposition Hole is suggested as a rejection criterion. Similarly, Deposition Holes showing visible grout would be rejected (TR-11-01, p. 829).

Review comments posed with respect to grouting plans to control water inflows into the Deposition Tunnels include:

1. Where Deposition Tunnels cross transmissive fractures, it is noted that there is risk that the tightness requirement (1.7 ℓ/min) cannot be achieved without post-grouting with silica sol (R-08-114, p. 68). However, the use of silica sol is also described as an unproven technology, with uncertainties concerning shrinkage after the grout has hardened and its long-term durability (> 5 years), both of which are described as “unknown” (R-08-114, p. 69).

2. With respect to post-grouting as a means to manage and mitigate high inflows into a Deposition Tunnel, R-08-114 states that there are no established and reliable strategies for post-grouting (p. 70). Succeeding with post-grouting is difficult and likely cannot be relied upon.

3. R-08-114 acknowledges that grouting with low pH grouts using conventional mixing equipment is not commonly practiced (p. 69).

4. Grout should only be considered as a short-/intermediate-term fix for reducing the transmissivity of fractures. Grout will eventually deteriorate or erode, returning the fracture to its original transmissivity. As previously noted, the durability of Silica Sol used to seal low transmissivity fractures is unknown beyond 5 years.

<u>B. Review Comments Related to Constructability:</u>

Review comments arising with respect to grouting are:

1. Although not included in the *Design Premises* in SR-Site (TR-11-01), the Underground Design Premises/D2 report (R-07-33) specifies a set of acceptable water inflows for the Deposition Tunnels, shafts and ramps (p. 51). These are assessed in the Grouting report (R-08-114) where it is concluded that there are many instances where these can’t be met using present grouting techniques. These include the uppermost 100 m of the rock mass through which the shafts and ramps will pass. Difficulties can be expected when intersecting water-bearing horizontal fractures, which could cause flushing, dilution and/or erosion of the grout (R-08-114, p. 68-69). The use of a grout curtain or ground freezing are suggested as means to reduce the degree of difficulty in driving the ramp and skip shafts through the first 100 m. These may add considerable costs and delays to the construction schedule.

2. Pre-grouting for the raise-bored ventilation shafts will involve grouting through deep boreholes (more than 470 m long), putting strict demands on drilling equipment and established grouting practices. Specifications are suggested for maximum drilling deviations of 0.3 to 0.5% (TR-08-114, p. 43). This will be challenging especially if foliation in the rock is present or where the boreholes are passing through fracture zones, as is the case for the ventilation shafts which are in close proximity to major deformation zones (Figure 2, BOTTOM). In addition, a number of practical aspects involving the handling of grout must be considered, including developing and testing procedures to pressurize and pump the grout, and avoid separation and dilution of the grout. If test trials prove unsuccessful, then

consideration may be required to construct the ventilation shafts using shaft sinking techniques where a more effective grouting of the rock mass can be ensured to meet the tightness requirements.

C. Recommendations (Category: Clarification/Submission): Clarification is requested as to the role of water inflow acceptance criteria for the different excavation types with regards to the *Design Premises* and *Safety Functions*. Similarly, what long-term function, if any, is the grout expected to play.

D. Recommendations (Category: Clarification/Submission): Updates are requested as to the long-term performance of low pH and silica sol grouts, together with tested procedures for their handling and use.

E. Recommendations (Category: Detailed Review/Further Review): Further review may be required as to experiences with grouting in crystalline rock from deep boreholes. The challenges of pre-grouting continuously from surface to the repository depths may force an alternative to raise-boring to construct the ventilation shafts. A risk assessment and cost-benefit analysis should be carried out.

4.7. Shotcrete and Reinforcement

A. Review Comments Related to Design Premises:

Relevant *Design Premises* discussed in discussed in SR-Site (TR-11-01) related to grouting are:

- *No continuous shotcrete in the Deposition Tunnels.*

Feedback to this *Design Premise* states that further quantification is required as to what constitutes "continuous shotcrete" (TR-09-22, p. 41). However, it is also stated that this quantification would be site specific as the distances would depend in part on where important water conducting fractures intersect the Deposition Tunnel. Comments/issues raised with respect to the use of shotcrete and reinforcement for ground control include:

1. Support in the Deposition Tunnels has been specified as being restricted to spot bolting or bolting with wire mesh for poorer quality rock (R-08-115, §5.4). This should be sufficient if favourable stress conditions are encountered. The exclusion of shotcrete (from the Deposition Tunnels) does significantly limit the options for managing spalling in the event spalling is more severe than expected. As noted above, it is not clear if shotcrete is to be completely excluded from the Deposition Tunnels or if restricted use below a quantified limit is allowable. The favourable orientation of the Deposition Tunnels relative to the stress field is cited as a justification for disregarding the need for reinforcement, i.e. shotcrete, to prevent spalling (R-08-115, p. 35). It should be cautioned that this does not apply to the advancing face of the Deposition Tunnels during their construction. Stress-induced spalling at the tunnel face is possible for the given stress-field orientation, and a potential hazard to workers. Consequently, there are possible scenarios where the conditions will require the use of shotcrete in the Deposition Tunnels to ensure worker safety.

2. A minimum reinforcement of 30 mm of continuous shotcrete is specified for all excavations other than the Deposition Tunnels to ensure safe working conditions. Is the use of continuous shotcrete in the main tunnel immediately in front of a Deposition Tunnel considered a similar scenario to the use of continuous shotcrete in the Deposition Tunnel itself? Does precluding the use of shotcrete in the Deposition Tunnels imply that the working conditions will be less safe?

B. Review Comments Related to Constructability:

Review comments arising with respect to the use of shotcrete and reinforcement for ground control are:

1. The rock conditions considered in the development of the support classes do not appear to take into account the possibility of horizontal jointing. As noted in R-08-115 (p. 50), there are numerous practical examples of how poorer-than-expected rock conditions produced contractual difficulties, cost overruns and schedule delays.

2. There does not appear to be any evaluation of the long-term integrity of the rock reinforcement. Rock bolts and mesh are susceptible to corrosion, and cement used to bond the rock bolts into place can lose their adhesive strength over time. What long-term role is the reinforcement meant to play with respect to the integrity and stability of the different excavation types (Deposition Tunnels, main tunnels, etc.)? As stated in R-08-115, there is limited experience with the long-term function of shotcrete and bolts, especially after using low pH grouts (p. 50).

C. Recommendations (Category: Clarification/Submission): Clarification is requested as to whether the analysis that concluded spalling is unlikely in the Deposition Tunnels due to their orientation relative to that of the stress field also considered spalling occurring at the tunnel face.

D. Recommendations (Category: Clarification/Discussion): A discussion would be beneficial regarding the construction challenges and implications for worker safety in placing restrictions on the use of shotcrete. Clarification is required as to quantifying what "continuous" means in the context of the *Design Premises* and how sensitive the reference design for the Deposition Tunnels is to the use of shotcrete.

E. Recommendations (Category: Detailed Review/Further Review): Further review should be carried out on the long-term performance of rock bolts, mesh, shotcrete and grout, and what implications their degradation will have on the long-term behaviour and stability of the excavations.

4.8. Investigation and Performance Verification During Construction

A. Review Comments Related to Design Premises:
To ensure the long-term safety and performance requirements of the repository are met, conformance of the construction and conditions encountered to the *Design Premises* must be verified. However, several *Design Premises* are stated in SR-Site (TR-11-01), in which a practical means to verify their conformance is not clearly evident, at least from a construction point of view. These include:

- *Deposition Holes should, as far as reasonably possible, be selected such that they do not have potential for shear larger than the canister can withstand. To achieve this, the EFPC criterion should be applied in selecting Deposition Hole positions.*
- *Fractures intersecting Deposition Holes should have sufficiently low connected transmissivity.*
- *Before canister emplacement, the connected effective transmissivity integrated along the full length of the Deposition Hole and as averaged around the hole, must be less than* 10^{-10} m^2/s.
- *Excavation induced damage should be limited and not result in a connected effective transmissivity, along a significant part (i.e. at least 20–30 m) of the disposal tunnel and averaged across the tunnel floor, higher than* 10^{-8} m^2/s. *Due to the preliminary nature of this criterion, its adequacy needs to be verified in SR-Site.*
- *Below the location of the top sealing, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than* 10^{-8} *m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones. There is no restriction on the hydraulic conductivity in the central area.*

In each of the above cases, issues/comments were raised with respect to their verification during construction. Specifically:

1. R-11-14 acknowledges that the *Design Premise* pertaining to the implementation of the EFPC is one that is “not directly measurable” (p. 19). Instead, fractures with full-perimeter intersections must be identified. Proposed investigation techniques include Deposition Hole and Tunnel mapping, although in some cases this will require fracture traces to be projected and correlated with other mapped traces. Radar and seismic reflection are also proposed to image the size and orientation of the fracture to aid in their identification and characterization (R-11-14, p. 44). Is radar effective if the fractures are dry? Does seismic provide the necessary resolution? What is the performance and reliability of seismic/radar in high saline or fresh groundwater conditions? Reliably detecting EFPC may prove difficult using geophysical techniques. Alternative means for determining the sizes of fractures intersecting Deposition Holes may be required.

2. R-11-14 reports plans to carry out hydraulic testing of fractures intersecting Deposition Holes through a pilot hole drilled prior to the full size hole to ensure they have sufficiently low connected transmissivity (p. 51). Given

the invasive nature of such tests, is there any risk of causing irreversible dilation (via slip) or increased transmissivity?

3. It not clear how the Design Premises based on allowable transmissivities or hydraulic conductivities associated with an excavation-induced damage zone will be measured and verified. Direct measurement would be difficult without invasive/undesirable techniques given that the enhanced permeability will be aligned parallel to the boundaries of the Deposition Holes and Tunnels. R-11-14 makes reference to seismic and radar reflection as a possibility (p. 64). However, this would require reliable correlations to be established between hydraulic conductivity and seismic/radar output. As stated in SR-Site, a method to inspect EDZ as well as a demonstration of the reliability of the method is needed (TR-11-01, p. 831). This need is emphasized in the feedback to the *Design Premise* on controlling EDZ (TR-11-01, §15.5.16), stating that transmissivities above the threshold value will start to affect risk.

4. TR-10-18 states that to ensure the long-term safety and performance requirements of the repository are met, parameters used to monitor the conformance to the design premises must be clearly identified and acceptance criteria quantified beforehand (TR-10-18, p. 28). However, several *Design Premises* are based on parameters that are hard or impossible to measure in a construction environment. The status of many of the verification methods put forward are summarized in R-11-14 as requiring some development or needing to be established altogether (p. 71-76).

<u>B. Recommendations (Category: Gaps/Omission)</u>: Means to verify conformance to the Design Premises in a construction environment have yet to be developed for a number of the premises. Much will depend on how characterization and monitoring data is implemented during construction. Licensing conditions should consider the limited Quality Assurance (QA) plan included in the License Application.

<u>C. Recommendations (Category: Clarification/Discussion)</u>: A discussion would be beneficial regarding whether a connected EDZ, in the event one develops along the walls of a Deposition Hole or in the floor of a Deposition Tunnel, should be treated as a fracture in the same way other large fractures are considered in the EFPC? The treatment of interconnected fractures that intersect and connect the respective (potential) EDZs of the Deposition Hole and tunnel are not discussed in the EFPC.

<u>D. Recommendations (Category: Detailed Review/Further Review)</u>: Further review should be carried out on the effectiveness and reliability of seismic and radar reflection (or other geophysical techniques) for detecting discriminating fractures in a construction/operations environment.

APPENDIX 1

Coverage of SKB reports

Table 3: Coverage of primary (assigned) reports reviewed.

Reviewed report	Reviewed sections	Comments
TR-11-01, Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project, Volume 1 and Errata	S1-S5 4.1-4.5 5.2, 5.6-5.8 10.2, 10.3. 5, 10.4.3-4 15.5.12, 15.5.15-19, 15.6.2, 15.6.6-7, 15.7.4	*Used as top level document.*
TR-10-52, Data report for the safety assessment SR-Site	1, 6.2, 6.4, 6.5	*Thermal and rock mechanics properties, and related data uncertainties.*
TR-10-48, Geosphere process report for the safety assessment SR-Site	3.1, 4	*Dependencies between processes.*
TR-10-18, Design, construction and initial state of underground openings	All	*Conformity of reference design to design premises. Qualitative risk assessment relative to initial state.*
TR-10-12, Design and production of the KBS-3 repository	3.5-3.9 4.7-4.9	*Functions of the engineered barriers and underground openings.*
TR-09-22, Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses	All	*Design premises that feed into SR-Site.*
TR-08-05, Site description of Forsmark at completion of the site investigation phase, SDM-Site Forsmark	5, 6, 7, 11, 12	*Used as top level document for site description.*
R-11-14, Framework for detailed characterisation for construction and operation	All	*Investigation programme to coincide with construction and operation.*

Table 4: Coverage of secondary (non-assigned) reports reviewed

Reviewed report	Reviewed sections	Comments
TR-10-21, Full perimeter intersection criteria	3, 6, 7, 8, 9	*Deposition Hole acceptance/rejection based on intersecting fractures.*
TR-07-01, Äspö Hard Rock Laboratory, Äspö Pillar Stability Experiment, Final report, Rock mass response to coupled mechanical thermal loading	8	*Method for determining crack initiation and spalling strength.*
TR-03-09, Thermal dimensioning of the deep repository Influence of canister spacing, canister power, rock thermal properties and nearfield design on the maximum canister surface temperature	All	*Oldest source found referring to 40 m separation distance between Deposition Tunnels (but still with no explanation why).*
R-09-39, Examination of the Excavation Damaged Zone in the TASS tunnel, Äspö HRL	All	*Experiment on which "no continuous EDZ" conclusion is partly based.*
R-09-04, Strategy for thermal dimensioning of the final repository for spent nuclear fuel	1, 5, 6	*Uncertainties in thermal dimensioning related to thermal properties.*
R-08-116, Underground Design, Layout D2	All	*Reference for layout, construction sequence. Spalling analysis reported in Appendix C.*
R-08-115, Underground Design, Rock mechanics and rock support	All	*Stress analysis of central area caverns and Deposition Tunnel profile.*
R-08-114, Underground Design, Grouting	All	*Details on grouting plans and uncertainties.*
R-08-113, Underground Design, Layout and construction plan	All	*Detailed description of construction plan and sequence.*
R-08-83, Site engineering report Forsmark, Guidelines for underground design Step D2	4, 9	*Ground types and behaviour, rock support and grouting.*
R-08-65, Thermal properties Forsmark Modelling stage 2.3 Complementary analysis and verification of the thermal bedrock model, stage 2.2	5	*Frequency distribution of thermal properties for RFM045.*

R-07-47, Thermal properties Site descriptive modelling Forsmark – stage 2.2	6	*Frequency distribution of thermal properties for RFM029.*
R-07-45, Geology Forsmark, Site descriptive modelling Forsmark stage 2.2	4, 5	*Source of reference geological model.*
R-07-33, Final repository facility, Underground design premises/D2	8, 10	*Acceptable water inflow to different underground openings*
R-07-31, Rock Mechanics Forsmark, Site descriptive modelling, Forsmark stage 2.2	All	*Rock mechanics data, including intact and rock mass properties, and in situ stress interpretations.*
R-07-26, Quantifying *in situ* stress magnitudes and orientations for Forsmark, Forsmark stage 2.2	All	*In situ stress data and interpretation.*
R-05-71, Potential underground stability (wedge and spalling)	All	*Stability analysis.*
P-07-206, Forsmark site investigation, Stress measurements with hydraulic methods in boreholes KFM07A, KFM07C, KFM08A, KFM09A and KFM09B	All	*Stress measurements using hydraulic fracture.*
P-04-186, Forsmark site investigation, Drill hole KFM01A, Thermal properties: thermal conductivity and specific heat capacity determined using the Hot Disk thermal constants analyser (the TPS technique) – Compared test	All	*Testing procedure for the TPS technique.*

APPENDIX 2

Suggested needs for complementary information from SKB

Essential questions to SKB requiring clarifications, complementary information, complementary data, etc., as discussed in detail in this review report include the following:

1. There does not appear to be a Deposition Hole rejection criterion that considers a non-persistent fracture intersecting a Deposition Hole that connects with a continuous EDZ/spalling along the floor of a Deposition Tunnel (or vice versa). Continuous EDZ should be treated jointly with the fracture intersection scenarios described in the EFPC. Similarly, the EFPC criteria only allows for fracture extent as mapped, not for the possibility that the fracture may propagate/coalesce during subsequent construction/operation activities in response to further stress changes and increasing rock temperatures. Further clarification should be requested.
2. It does not appear that a project cost-schedule risk assessment has been carried out with respect to construction. A qualitative risk assessment is reported with respect to geohazards, however, schedule delays and cost overruns should also be considered. A request for complimentary information should be made.
3. A fully demonstrated testing of the loading of the canisters at full weight and for the buffer geometry/tolerances specified would be required as a proof of concept with respect to constructability. Repeatability of the procedure should be included to determine the percentage of successful completions per attempt. A request for complimentary data on the testing carried out to date should be requested.
4. Means to verify conformance to the Design Premises in a construction environment have yet to be developed for a number of the premises. Much will depend on how characterization and monitoring data is implemented during construction. Licensing conditions should consider the limited Quality Assurance (QA) plan included in the License Application.
5. The assessment of likelihood of encountering sub-horizontal brittle fracture zones at the repository depth does not appear to be considered in the qualitative risk analysis. This appears to be based on the identification of only three gently dipping deformation zones in the Site Descriptive Model. Clarification should be requested as to the resolution of the detection methods used (seismic reflection, single-hole interpretations) with respect to the minimum sub-horizontal deformation zone detectable.
6. Is the exclusion of Deposition Holes in low thermal conductivity rock included in the Deposition Hole acceptance/rejection criteria? Do the

analyses of loss of Deposition Hole positions account for the likelihood of amphibolite lenses occurring more frequently than indicated? Clarification should be requested.

7. What methodology will to be used to reliably characterise less common rock types (e.g. amphibolites lenses, vuggy granite, etc.) in near-field during construction? Complementary information should be requested.
8. Clarification should be requested as to the mechanism by which the trend of the maximum horizontal stress is interpreted to decrease in gradient at 400 m depth but the trend of the minimum horizontal stress remains linear.
9. Are the stresses measured in boreholes KFK001/DBT1 and KFK003/DBT3 located outside the target volume and in FFM04 applicable to the repository volume? How would the stress interpretation change if these data were excluded? Clarification should be requested.
10. Complimentary data should be requested with respect to the conclusion that EDZ, if it develops, will not be continuous. Is the Äspö experiment on which this conclusion is based only applicable to blast-induced damage and not excavation-induced damage resulting from the redistribution of stress and stress concentrations?
11. Complimentary information should be requested as to the source and basis for the 40 m centre-to-centre separation distance between Deposition Tunnels. This appears to be based on thermal dimensioning. Have stress analyses been performed that consider the influence of excavation sequencing on the development of stresses around/between the Deposition Tunnels and boreholes as the repository is constructed? The analyses reported appear to be based on the stresses between multiple Deposition Holes in a single Deposition Tunnel.
12. Is the 30-35% overbreak limit expressed in the *Design Premises* for Deposition Tunnels excessive or incompatible with the requirement to minimize construction damage? Can this be reduced to improve overall quality control? Complimentary information should be requested. If the specified total volume and section area overbreak limits are maintained, then should a third linear limit be added to ensure local exceedance is minimized? For example: “Acceptable largest linear overbreak (measured normal to design profile) should not exceed the nominal 0.25×Radius for a circular profile or 0.13×Span for a square profile”.
13. The potential for adverse effects from blasting on the deposition works are accounted for in the repository layout by imposing separation and safety distances. Are similar considerations required for other vibration sources, for example heavy vehicles carrying heavy canisters or hauling waste rock along uneven surfaces? Complimentary information should be requested.
14. Complimentary information should be requested as to the risk associated with having the ventilation passing from the deposition areas into the excavation areas, as required by the Linear Development Method sequencing, in the event of an accident involving a canister. Is this a potential issue identified in the risk assessment of worker safety or in the development of safety protocols?
15. Clarification should be requested as to references in the different construction plan reports to the use of a “TBM”. Is this in reference to a tunnel boring machine?

16. Clarification should be requested as to the strictness of the Deposition Hole and buffer installation tolerances. How critical are they to the safety case? Can they be modified to allow for slightly greater tolerances in order to improve the success rate of installation? If critical, would it be better to install the canister and buffer blocks together as an integrated package allowing the integrity of the full engineered barrier to be verified before installation in the Deposition Holes?
17. Is there a limit on the amount of overbreak that occurs in the Deposition Holes? Should overbreak be included in the Deposition Hole acceptance/rejection criteria? Complimentary information should be requested.
18. Clarification should be requested as to the role of water inflow acceptance criteria for the different excavation types with regards to the Design Premises and Safety Functions. Similarly, what long-term function, if any, is the grout expected to play.
19. Complimentary data should be requested as to the long-term performance of low pH and silica sol grouts, together with tested procedures for their handling and use.
20. Clarification should be requested as to whether the analysis that concluded spalling is unlikely in the Deposition Tunnels due to their orientation relative to that of the stress field also considered spalling occurring at the tunnel face.
21. Complimentary information should be requested regarding plans to develop contingency actions in response to adverse ground conditions, if encountered, may be beneficial. Clarification as to how these will couple Design Premise requirements with worker safety and construction cost requirements should be established.
22. Some of the uncertainties to be managed by the Observational Method will not be resolved until after construction and operations are well underway (e.g. presence of adverse geology/fractures in the farther reaches of the repository). What are the implications if the rejection ratio of Deposition Holes doubles (triples) in the planned second half of the repository from experiences in the first half of the repository when options for adapting are significantly more limited? Complimentary information should be requested.
23. A single unified summary of the combined set of measurements, analyses and assumptions (including filtering logic) for the determination of the *in situ* stress regime (trends and ranges) should be requested. The current documentation is complex and leads to the risk of overly confident stress specifications.
24. Complimentary data should be requested regarding the selection of the representative *in situ* stress and associated ranges (likelihoods) at the repository horizon, as well as provisions for follow-up refinement and implications for design of realistic deviations from this base case (both deviations from the average predicted stress field and local stress anomalies).
25. Clarification should be requested regarding the distinction and separation of construction damage (CDZ) from stress-induced excavation damage (EDZ), as these apply differently with respect to the effectiveness of the

mitigation and management measures proposed (e.g., smooth wall blasting). Also to be considered is the excavation fracture zone (EFZ), also referred to as the highly damaged zone (HDZ).

26. Would installing the canister and buffer blocks together as an integrated package negate the need for the bottom plate? Complimentary information should be requested regarding the sensitivities of the rock/buffer and buffer/canister interfaces with respect to the Design Premises and Safety Functions.
27. Complimentary information should be requested regarding the construction challenges and implications for worker safety in placing restrictions on the use of shotcrete. Clarification should be requested as to quantifying what "continuous" means in the context of the Design Premises and how sensitive the reference design for the Deposition Tunnels is to the use of shotcrete.
28. Clarification should be requested regarding whether a connected EDZ, in the event one develops along the walls of a Deposition Hole or in the floor of a Deposition Tunnel, should be treated as a fracture in the same way other large fractures are considered in the EFPC? The treatment of interconnected fractures that intersect and connect the respective (potential) EDZs of the Deposition Hole and tunnel are not discussed in the EFPC.

APPENDIX 3

Suggested review topics for SSM

Topics requiring substantial additional work on the part of SSM and SSM's external experts during the main review phase are suggested as follows:

1. Further review may be required as to the likelihood and impact of increased width and/or change in position of the major deformation zones on the reference design and underground layout design with respect to increased impact of respect distances within and around the deposition area.
2. Further review may be required as to whether increased tectonic disturbance and poorer rock mass conditions than accounted for can be expected along the western margin of the repository, and what impact this may have on the constructability and safety of the transport tunnels and ventilation shafts.
3. Further review may be required as to the spalling strengths adopted, the corresponding uncertainty, and whether this should be considered as an uncertainty/geohazard in the qualitative risk analysis of site uncertainties on design. If so, this uncertainty should be considered in tandem with the uncertainty regarding *in situ* stress.
4. Are there scenarios that the Observational Method won't be able to react to in a manner that ensures worker safety, project economics and/or the Design Premises being met, and how do the options for adaptation change with different stages of repository construction and operations? Are there operational and post-closure considerations that cannot be tested through the Observational method?
5. Further review may be required for the currently adopted stress regime at the repository location, including the impact of realistic deviations from this assumption coupled with the uncertainties in strength and stiffness (including local geological heterogeneities).
6. There is limited experience, both experimental and applied, with respect to time-dependent behaviour and long-term evolution of stress-induced brittle fractures. A more detailed and thorough review of the applicability of concepts relating to sub-critical crack propagation, stress corrosion and long-term strength degradation and performance of crystalline rock under sustained compressive loading on stress-induced fractures in the EDZ is suggested.
7. Further review may be required as to how the construction sequence factors into the geohazard risk analysis. The farther extents of the repository will not be penetrated by excavation workings until after 20 years of construction. How does this impact the overall risk of ensuring the availability of the required Deposition Holes, if the geological conditions encountered are more adverse than expected? For example, would the construction of the Main Tunnels, Transport Tunnels and Short-cut Tunnels before proceeding to the construction of the Deposition Areas be a feasible measure to reduce uncertainties and confirm the design assumptions?

8. Further review may be required as to experiences with grouting in crystalline rock from deep boreholes. The challenges of pre-grouting continuously from surface to the repository depths may force an alternative to raise-boring to construct the ventilation shafts. A risk assessment and cost-benefit analysis should be carried out.
9. Further review should be carried out on the long-term performance of rock bolts, mesh, shotcrete and grout, and what implications their degradation will have on the long-term behaviour and stability of the excavations.
10. Further review should be carried out on the effectiveness and reliability of seismic and radar reflection (or other geophysical techniques) for detecting discriminating fractures in a construction/operation environment.
11. An independent assessment of the geohazard risks and their likelihood of occurrence may be required. This should maybe include an independent analysis of Deposition Hole rejection scenarios relative to one or more geohazard risks being realized.
12. An analysis of cumulative error propagation is required tracing assumptions and uncertainties in defined stress regime through EDZ assessment and support calculations.
13. Uncertainties in stress and spalling strength may combine to create a likelihood of stress-induced spalling. Quick scoping calculations within the ranges of uncertainties suggest spalling could be significant. This similarly extends to the uncertainties in thermal conductivity and coefficient of thermal expansion, which likewise may combine to increase the extent of thermal spalling.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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