Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Erik Eberhardt
Mark Diederichs

Technical Note

2014:07

Review of the geological mapping and geophysical measurement techniques for the determination of critical properties around deposition holes

Main Review Phase

Report number: 2014:07 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspektiv

Bakgrund

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

Projektets syfte

Det övergripande syftet med projektet är att ta fram synpunkter på SKB:s säkerhetsanalys SR-Site för den långsiktiga strålsäkerheten för det planerade slutförvaret i Forsmark. Denna Technical Note innehåller en utvärdering av prestation och tillförlitlighet av de geologiska och geofysiska metoder som SKB föreslår för att mäta de geomekaniska parametrar som är kritiska för att bestämma acceptans av deponeringshål under slutförvarets drifttid.

Författarnas sammanfattning

Denna Technical Note redovisar resultaten av en detaljerad utvärdering av de geologiska och geofysiska metoder som föreslås av SKB med avseende på metodernas förmåga, upplösning, prestanda, tillförlitlighet och robusthet att mäta de kritiska geomekaniska parametrarna vid val av deponeringshål under slutförvarets drifttid. Specifika frågor fokuserar på metoder för att upptäcka diskriminerande sprickor som skär deponeringshålspositioner och som kan påverka den långsiktiga säkerheten genom att möjliggöra antingen skjuvrörelser som överstiger kapslarnas hållfasthet, eller höga vatteninflöden som kan leda till kanalbildning och erosion av buffertmaterial. Övriga frågeställningar som har adresserats är: i) möjligheten att kunna mäta utbredning av skadezonen (EDZ) runt deponeringstunnlar och deponeringshål samt att säkerställa att transmissiviteten inte överstiger de gränser som krävs för att uppnå den långsiktiga säkerheten, och ii) identifieringen av mindre förekommande bergarter med lägre värmeledningsförmåga som kan påverka den långsiktiga säkerheten genom att temperaturen i bufferten överstiger gränsen vid vilken den förlorar sin säkerhetsfunktion.

De viktigaste resultaten från denna granskning är följande:

- Konservatism krävs vid tillämpningen av ”Extended Full Perimeter intersection Criteria” (EFPC). Denna robusta metod behövs på grund av alla begränsningar i användningen av övriga geologiska och geofysiska metoder för att identifiera potentiellt diskriminerande sprickor. Nyligen utförda studier av Posiva (Finland) visar att reflektionsseismik har dålig förmåga att upptäcka stora tunnelskärande sprickor och att markradar (Ground Penetrating Radar, GPR) ensamt inte kan användas för att välja bort deponeringshålspositioner på grund av långa sprickor.
- Baserat på planerat utförande av slutförvaret, från det centrala området och utåt, kommer osäkerheter med avseende på ogynnsamma geologiska företeelser samt ökat antal av diskriminerande

sprickor i de perifera delarna av förvaret inte att kunna fastställas förrän efter tunneldrivningen är i full gång. Detta kan begränsa effektiviteten för Observationsmetoden för att hantera geologiska osäkerheter eftersom ett ökat bortfall av deponeringshål i de yttre delarna av slutförvaret begränsar möjligheterna till anpassning av slutförvarets layout betydligt.

- Även om en delmängd av de kritiska sprickor som identifierats av EFPC sannolikt skulle kunna vara hydrauliskt aktiva, krävs en direkt mätning av inflöden i deponeringstunnel och deponeringshål för att kontrollera att de tillämpliga konstruktionsförutsättningarna är uppfyllda. Uppföljning och utvärdering av inflödesmätningar i deponeringstunnel och deponeringshål måste också övervägas för att ta hänsyn till möjligheten att flödesförhållanden förändras med tiden. Prestationsvärdering bör utvecklas för att säkerställa att deponeringshål som inledningsvist bedöms som acceptabla inte efteråt hyser höga inflöden på grund av en förändring av vattengenomsläppligheten i spricknätet. Prestationsvärdering är viktigt för att bygga förtroende för metoderna hos intressenterna.
- Det nuvarande antagandet gällande EDZ kan vara icke-konservativt. Antagandet involverar uppskattningar och osäkerheter hos bergspänningsmagnituder och riktningar samt inneboende osäkerheter i mätningen av tröskeln för sprickinitieringen och av andra materialparametrar. Därför är mätning av förekomsten av EDZ nödvändig när uppförandet av slutförvaret inleds.
- Högfrekvent GPR har en potentiell tillämpning som ett rutinmässigt operativt verktyg för mätning av EDZ på tunnelskala, i synnerhet för djupbestämning och rumsfördelning. Metoden har dock betydande begränsningar vid detektering av långa sprickor. Resistivitetsmätningar kan mäta djupet för EDZ med viss tillförsikt, men varierande fukthalt i EDZ kan resultera i otillförlitliga resultat. Det finns utmaningar med att få effektiva och upprepningsbara mätningar på grund av kopplingsproblem. Refraktionsseismik kan upptäcka EDZ men är operativt inte praktiskt tillämpningsbar i tunnlarna.
- SKB:s karaktäriseringsprogram för att upptäcka underordnade bergarter under uppförande av slutförvaret är förenlig med de metoder som utnyttjas på liknande projekt inom slutförvaring av kärnavfall. Fokus bör ges till metoder för att uppskatta bergmassans termiska ledningsförmåga baserat på densitet och P-vågshastigheter. Dessa parameterar erhålls genom geofysiska borrhålsloggningsmetoder samt labbtester. Även tillämpningen av datainterpolation samt extrapolation med hjälp av kriging bör testas om rumslig korrelation observeras på plats.

Projektinformation

Kontaktperson på SSM: Flavio Lanaro
Diarienummer ramavtal: SSM2011-3641
Diarienummer avrop: SSM2013-2504
Aktivitetsnummer: 3030012-4059

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 and provide expert opinion on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of this project is to provide review comments on SKB's post-closure safety analysis in SR-Site for the proposed repository at Forsmark. This Technical Note contains an evaluation of the performance and reliability of the geological and geophysical methods proposed by SKB for measuring the geomechanical parameters critical for determining deposition hole acceptability during repository operation.

Summary by the authors

This Technical Note reports the findings of a detailed evaluation of the geological and geophysical methods proposed by SKB with respect to their ability, resolution, performance, reliability and robustness to measure the geomechanical parameters critical for determining deposition hole acceptability during repository operation. Addressed are specific questions focusing on the detection of discriminating fractures intersecting deposition hole positions that may impact long-term safety by enabling either shear movements in excess of those the canisters are designed to withstand, or high water inflows that may lead to piping and erosion of the buffer material. Also addressed are: i) the feasibility of measuring the excavation damage zone (EDZ) around the deposition tunnels and deposition holes to ensure that transmissivities do not exceed the values required for long-term safety, and ii) the detection of less common (subordinate) rock types with lower thermal conductivity properties that may impact long-term safety by enabling temperatures in the buffer to exceed design threshold values.

Key findings from this review include the following:

- Conservatism is required in applying the Extended Full Perimeter Criterion (EFPC) due to the need for a robust method to identify potentially discriminating fractures coupled with limitations in the use of geological and geophysical techniques. Recent working reports from Posiva (Finland) conclude that seismic reflection performed poorly in detecting large tunnel-crosscutting fractures and that Ground Penetrating Radar (GPR) alone cannot be used for acceptance/rejection of deposition hole positions.
- Based on the planned construction of the repository from the central area outwards, uncertainties in the presence of adverse geology and increased number of discriminating fractures in the farther reaches of the repository will not be resolved until after

construction and operations are well underway. This may limit the effectiveness of the use of the Observational Method to manage geological uncertainties as it is possible that increases in the rejection ratio of deposition holes could be encountered after the options for adapting are significantly more limited.

- Although a subset of critical fractures identified by the EFPC would likely be hydraulically active, direct measurement of deposition tunnel and deposition hole inflows is required to verify conformance with the relevant Design Premises. Any monitoring and assessment of deposition tunnel/hole inflows need to also consider the potential for changing flow conditions. Performance assurance measures should be developed to ensure that deposition holes initially assessed as being acceptable do not afterwards experience high inflows due to a change in the connectivity of the fractures intersecting the deposition hole. Performance assurance will build trust with the stakeholders.
- The current assumptions involved in EDZ prediction may not be conservative. This includes the estimation of stress magnitudes, uncertainties in direction, and inherent uncertainties in the measurement of crack initiation threshold and other material parameters. Therefore, verification is required once construction of the repository begins.
- High frequency GPR holds promise as a routine operational tool for tunnel scale EDZ depth determination and spatial distribution assessment. It has significant limitations for detection of more distal fractures. Resistivity surveying can detect EDZ depth with some confidence although the results may be unreliable if the moisture content within the EDZ varies. There are challenges with effective and repeatable data collection due to coupling issues. Seismic refraction can detect EDZ but is not an operationally practical tool.
- SKB's characterisation programme for detecting subordinate rock types during construction is consistent with methods being utilized on similar nuclear waste disposal projects. Consideration should also be given to estimating rock mass thermal conductivities based on density and P-wave velocities obtained by geophysical borehole logging methods and laboratory testing. The application of interpolation and extrapolation techniques by means of kriging should also be tested if spatial correlation is observed.

Project information

Contact person at SSM: Flavio Lanaro

Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

Author: Erik Eberhardt and Mark Diederichs
Fisher & Strickler Rock Engineering LLC, Radford, VA, USA

Technical Note 47

2014:07

Review of the geological mapping and geophysical measurement techniques for the determination of critical properties around deposition holes

Main Review Phase

Date: September 2013
Report number: 2014:07 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Contents

1. Introduction

This Technical Note reports the findings of a detailed evaluation of the geological and geophysical methods proposed by SKB with respect to their ability, resolution, performance, reliability and robustness to measure the geomechanical parameters critical for determining deposition hole acceptability during repository operation. Addressed are specific questions raised by SSM, together with relevant supporting analysis and technical material, focussing on:

- The detection of large fractures intersecting deposition hole positions that may impact long-term safety by imposing shear movements in excess of those the canisters are designed to withstand in response to an earthquake event.
- The detection of critical, conductive fractures intersecting deposition hole positions that may impact long-term safety through high water inflows that may lead to piping and erosion of the buffer material.
- The feasibility of measuring and quantifying the excavation damage zone damage (EDZ) and depth of spalling in the rock around the deposition tunnels and deposition holes to ensure that transmissivities do not exceed those required for long-term safety.
- The detection of less common (subordinate) rock types with lower thermal conductivity properties that may impact long-term safety by enabling temperatures in the buffer to exceed design threshold values.

SKB's Design Premises are used as a framework for the review, comparing the detection resolution and reliability of the geological and geophysical measurement methods proposed in SKB's construction and operation characterisation plan (R-11-14), to the safety-related performance indicators formulated for the deposition holes and their interaction with the engineered barriers in SR-Site (SKB TR-11-01). The experiences reported by SKB in their related technical reports as well as their stated future development plans are reviewed, including recent results from on-going research and development projects carried out in collaboration with Finland's counterpart organisation responsible for the final disposal of spent nuclear fuel, Posiva Oy.

The report concludes with several recommendations to SSM regarding the limiting aspects of the techniques proposed by SKB. These should be addressed and demonstrated before they can be reliably employed to verify that the Design Premises are being met during repository construction and operation.

2. Overview on SKB’s Deposition Hole Acceptance Criteria

2.1. SKB’s Design Premises

The SKB reference design and layout of the KBS-3 repository incorporates a series of safety related specifications, termed Design Premises, which are described as fundamental design constraints that form the basis for demonstrating repository safety (SKB TR-11-01, p. 19). These apply to the different design components: canisters, buffer, deposition holes, deposition tunnels, backfill, etc.

Those relating specifically to the acceptance or rejection of deposition holes are listed in Table 1.

SKB subsequently reviewed these Design Premises with respect to the specific reference design assessed in SR-Site. Based on this assessment, they provided “feedback” as to recommended modifications that should be considered in safety analyses for future licensing steps (SKB TR-11-01, Sec. 15.5). These are described in the following subsections with respect to deposition hole acceptability.

2.2. SKB’s feedback to SR-Site on mechanical stability and EFPC

The Design Premises regarding mechanical stability address the scenario where detrimental shear movements may occur as a consequence of an earthquake event, which in turn may induce secondary movements in fractures intersecting deposition holes (SKB TR-11-01, p. 817).

At the repository scale, SKB feedback regarding the 100 m respect distance between deposition hole positions and deformation zones longer than 3 km, judges this Design Premise as being acceptable. Allowance is made that this criterion may be revised depending on results from future investigations at the Forsmark site in characterizing the actual extents of the major deformation zones and their splays.

At the deposition tunnel scale, the Design Premise applies the Extended Full Perimeter Criterion (EFPC) to exclude deposition holes with the potential for large shear. This is coupled with the Design Premise for canister stability in shear (SKB TR-11-01, p. 821):

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

SKB’s feedback concludes that the probability of encountering shearing greater than 5 cm is very low, and therefore the specified shear displacement serves as an adequate criterion (SKB TR-11-01, p. 822). However, an allowance is also made for

Table 1: Design Premises related to properties in and around deposition holes (SKB TR-09-22).

Deposition Hole Criteria	Property to be Designed	Relevant Design Premise for Long-Term Safety
Mechanical Stability	Deposition holes – respect distance to deformation zones	*Deposition holes are not allowed to be placed closer than 100 m to deformation zones with trace length longer than 3 km.*
	Deposition holes – intersecting fractures (mechanical properties)	*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.*
Hydrological & Transport Conditions	Deposition holes - inflow	*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.
	Deposition holes – intersecting fractures (hydrogeological properties)	*Fractures intersecting the deposition holes should have sufficiently low connected transmissivity.*
	Deposition holes – transmissivity of spalling and EDZ	*Before canister emplacement, the connected effective transmissivity integrated along the full length of the deposition hole wall and as averaged around the hole, must be less than* 10^{-10} m^2/s.
	Deposition tunnel – EDZ	*Excavation induced damage should be limited and not result in a connected effective transmissivity, along a significant part (i.e. at least 20–30 m) of the deposition tunnel and averaged across the tunnel floor, higher than* 10^{-8} m^2/s.
Thermal Properties	Deposition holes – spacing (thermal dimensioning)	*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 reformulation of this criterion if a more suitable one can be established; SKB sees the EFPC as being overly conservative (SKB R-11-14, p. 73). Thus the feedback for this Design Premise suggests the following modification (SKB TR-11-01, p. 828):

> *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 EFPC criterion is a tool to identify such fractures, but can be replaced or complemented by other tools in cases where the application of such*

tools is shown not to increase the risk contribution. (Struck-out text is included to show the change to this Design Premise preferred by SKB).

2.3. SKB's feedback to SR-Site on hydrological conditions and EDZ

The Design Premises specifying the hydrological conditions of the deposition holes address the potential for piping erosion and buffer loss due to high flows. The development of significant EDZ and spalling is also considered as a means by which the maximum allowable transmissivity set out in the design may be exceeded.

The criterion specified to avoid piping in the buffer resulting from flow in fractures intersecting the deposition holes, i.e. < 150 m^3 of water entering deposition hole before buffer saturation, was deemed appropriate (SKB TR-11-01, p. 829). However, it was suggested that a more practical design rule was needed, requiring further research and development.

The criterion specifying that fractures intersecting the deposition holes should have sufficiently low connected transmissivity does not include a specific threshold value. Addressing this, the SKB feedback suggests the following reformulation (SKB TR-11-01, p. 829):

> *Avoid deposition holes intersected by connected transmissive fractures capable of producing higher inflows than 0.1 ℓ/min.*
>
> *Deposition holes intersected by fractures showing visible grout should also be rejected.*

The SKB feedback further suggests that these criteria be combined with the application of the EFPC for fractures showing potential for groundwater flow (i.e., completely healed fractures would not be considered). It is suggested that the EFPC can be used as an indicator for fractures capable of high flows once the repository is sealed and saturated (SKB TR-11-01, p. 152).

SKB feedback regarding the influence of EDZ on transmissivity along the deposition holes (must be less than 10^{-10} m^2/s) accounts for the potential for excavation damage as well as stress- and thermal-induced spalling. The latter (thermal-induced spalling) is suggested as being mitigated by the counter pressures that will be exerted by the swelling buffer and bentonite pellets (SKB TR-11-01, p. 830). The feedback concludes that there is no reason to revise this Design Premise.

It should be noted that a similar Design Premise also applies to EDZ in the deposition tunnels (SKB TR-11-01, p. 831):

> *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.*

Feedback to this criterion confirms that the suggested upper limit of connected transmissivity along the deposition tunnels is adequate. Connected EDZ transmissivity above this value will start to affect risk and needs to be avoided (SKB TR-11-01, p. 831).

2.4. SKB's feedback to SR-Site on thermal dimensioning and subordinate rock types

The thermal properties of the rock and deposition hole spacing are the key parameters influencing the peak buffer temperature. SKB feedback regarding the maximum temperature level in the buffer (< 100 °C), suggests that there is no immediate need to revise this Design Premise. The thermal analysis is taken to demonstrate that the peak temperature criterion incorporates an adequate safety margin, even when the spatial variability of the rock thermal properties is taken into account (SKB TR-11-01, p. 830-831).

2.5. Summary on SKB's criteria for acceptance/rejection of deposition holes

Together, the Design Premises set out the properties that the deposition holes should have in order to work with the engineered barriers to ensure the long-term safety functions of the repository are met (SKB TR-10-18, p. 17). As such, they represent a set of specifications that will require detailed investigation and documentation during construction and operations to verify conformance.

To ensure the site-specific conditions meet the Design Premises, SKB R-11-14 describes the detailed investigation programme that will be applied during construction and operation. This will involve a series of targeted investigations and decision points regarding deposition hole acceptability on which the final decision for canister emplacement will be based (Figure 1).

The following sections in this report review SKB's characterisation and investigation plans as they apply to deposition hole acceptance/rejection, outlining the status and development needs presented in SKB R-11-14. As requested for this

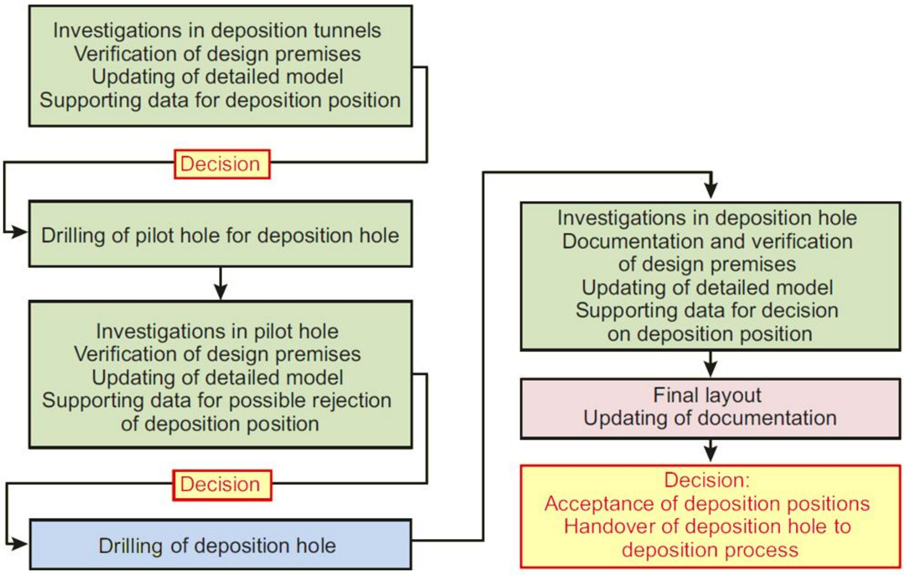

Figure 1: Schematic work flow for excavation and approval of deposition hole following approval and construction of a deposition tunnel. Modified after SKB R-11-14, p. 47.

review assignment, specific focus will be placed on evaluating the ability, performance, resolution and robustness of the geological mapping and geophysical measurement techniques proposed by SKB as a means to verify conformance to the Design Premises as they pertain to deposition hole acceptance. This includes a comprehensive review of the scientific literature and work done in other nuclear waste disposal programmes. Also considered are the expected scientific and technical developments for these methods in the coming decades.

3. Performance of Geological and Geophysical Methods: EFPC

3.1. SKB's plan on mechanical stability

The identification of large fractures is a key requirement to fulfil SKB's Design Premises regarding the mechanical stability of the deposition holes (Table 2).

The issue of mechanical stability links SKB investigations on the size of fractures that can accommodate slip greater than what the canisters can withstand with the criterion that can be used to identify these fractures in a construction environment. This applies to one of the three identified failure modes for the canisters, namely shear across a deposition hole triggered by an earthquake event (SKB TR-09-22, p. 25). The Design Premise formulated for this case is that the canisters should be able to withstand 5 cm of shear at 1 m/s (SKB TR-09-22, p. 11). This magnitude is then extended to a maximum slip criterion of 5 cm of fracture displacement across a deposition hole regardless of the shear velocity and intersection geometry (SKB TR-08-11, p. 3).

Table 2: Characterisation plans for meeting the Design Premises related to the EFPC and mechanical stability (SKB R-11-14).

Design Premise	Role of Detailed Characterisation	Status and Development Need for Methods
<u>Mechanical Stability</u>:		
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. (An allowance is made that the EFPC may be replaced in future with an alternative criterion judged to be more realistic for determining which fractures are long enough to shear a canister).	SKB plans to map the walls, ceilings and floors of the deposition tunnels with sufficient accuracy to permit detection of "large fractures" that can be followed around the entire tunnel perimeter. Furthermore, "large fractures" that intersect five or more deposition holes will be identified by investigations from the tunnel or in pilot holes, for which progressive modelling is an essential element. Geophysical methods (radar and seismic) and hydraulic tests will also be employed. A step-by-step evaluation procedure will be used to avoid the drilling of deposition holes in positions that cannot be accepted.	SKB deems the existing method for tunnel mapping to be adequate. Further development based on radar and seismic methods is required for early identification and characterisation of "large fractures" that intersect five or more deposition holes, but also of methodology that utilises different types of hydraulic methods. The development work will identify which fracture properties can be detected by a given investigation method. The application of the methods in the different steps will further be studied for the purpose of arriving at an expedient method package. A methodology for final mapping of fractures in deposition holes has not been established, but is considered possible to develop without any great difficulty.

SKB TR-08-11 summarizes the investigations carried out to define the shear processes related to an earthquake event that could result in damage to the canisters. Processes related to the direct intersection of the deposition hole with a seismogenic fault or fracture directly connected to a seismogenic fault can be mitigated based on the Design Premise stipulating a respect distance of 100 m from deformation zones with trace lengths longer than 3 km. According to the site descriptive model (SKB TR-08-05, p. 401-402), the repository volume is intersected by four possibly instable known deformation zones greater than 3 km. SKB concludes that the risk that there may be other, unidentified deformation zones of this size is very low (SKB R-11-14, p. 43).

Deformation zones that are vertical to steeply dipping (the majority at the site) have been identified based largely on low magnetic lineaments in airborne magnetic data (SKB R-07-45, Table 5-2). The uncertainty in the spatial position from the airborne data is ±20 m (SKB R-07-45, p. 106). This perhaps raises the question whether the respect distance should be 120 m if this uncertainty cannot be narrowed through the investigations to be carried out during construction. It is important to note that this respect distance should be the true (minimum) distance in three-dimensions and not the apparent distance evident in the horizontal layout plan.

Deformation zones that are gently dipping (< 45°) were detected based on surface seismic reflection data integrated with borehole data (SKB R-07-45, p. 111). An estimate of the uncertainty in the spatial position of a reflector is reported to be ± 15 m (SKB R-07-45, p. 111). Confidence in detection is reported to be high for more than 60% of the deformation zones identified in the site descriptive model using these techniques (SKB R-07-45, p. 158). SKB therefore judges that the detailed characterisation relevant to the respect distance can be carried out using known and available investigation techniques (SKB R-11-14, p. 72). The use of pilot holes (SKB R-11-74, p. 37) and seismic reflection (SKB R-11-14, p. 48) are cited in conjunction with construction of the transport and main tunnels to determine the precise locations of the deformation zones.

In conducting these investigations, it will be important to consider the cumulative uncertainty related not only to determining the precise locations of the deformation zones at depth, but also accounting for the variability in their thickness and structural architecture. For example, SKB notes that confidence in the modelled thickness of the deformation zones will depend entirely on the number of borehole intersections and their spatial distribution (SKB R-08-83, p. 25). This is illustrated in Figure 2, which suggests that the 100 m respect distance based on the modelled deformation zone may need to be extended if the thickness at the repository depth happens to be wider than the modelled thickness.

Furthermore, SKB specifies that the 100 m respect distance should be taken as the perpendicular distance from the boundaries of the modelled deformation zones (SKB TR-10-18, p. 35). Establishing this outer boundary based on fracture frequency will have some variability depending on the number and orientation of the investigation boreholes. Adding to this variability is that the architecture of most deformation zones is asymmetric, and thus it is likely that the core (where strain will initially localize during a seismic event) may be closer to one boundary defining the 100 m respect distance than the other.

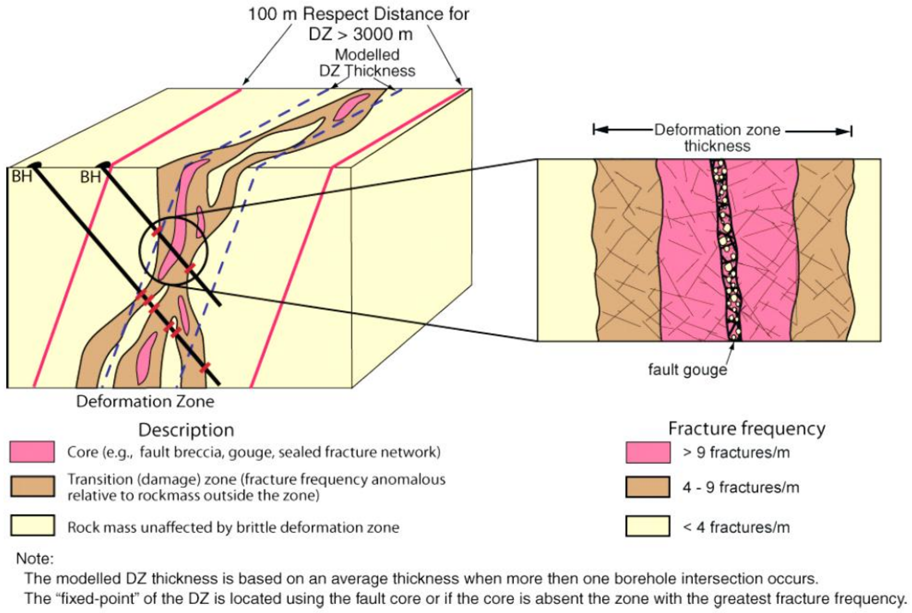

Figure 2: SKB definitions of modelled deformation zone thickness and respect distance and possible variability relative to the use of borehole investigations. From SKB R-08-83 (p. 26).

The other scenario considered is where a deposition hole is intersected by a fracture at some distance from the seismogenic fault, but that slip can still occur as a result of the dynamic effects and stress redistribution from an earthquake on the distal fault (SKB TR-08-11, p. 137). The Design Premise to mitigate this scenario relies on the *Extended Full Perimeter Criterion* (EFPC). This criterion specifies two discriminating conditions (SKB R-11-14, p. 19):

i) A canister position must not be intersected by a fracture or deformation zone that can be followed around the full tunnel perimeter of the deposition tunnel, referred to as a Full Perimeter Intersection (FPI), (Figure 3a); and

ii) If a fracture or deformation zone intersects five or more canister positions, they must be rejected (Figure 3b).

Assuming five, this criterion will detect fractures with radii exceeding 12 m, assuming a 6 m canister spacing (SKB TR-10-21, p. 12-13). Application of the first part of the criterion, the FPI, encompasses even smaller fractures with radii as small as 3 m, for a 4.8 m high deposition tunnel (SKB TR-10-21, p. 22).

These compare against the critical radii of 50 m adopted in SKB R-04-17 (p. 43) and 62.5 m in SKB TR-08-11 (p. 120) as the minimum fracture size capable of exceeding the 5 cm damage threshold for a 100 m minimum respect distance as required by the Design Premises. Note that the latter value of 62.5 m is assumed based on a linear scaling of values calculated for a sub-horizontal fracture and earthquake event occurring along a deformation zone with trace length greater than 5 km (M_w 7.5). Other conditions including an earthquake occurring along a deformation zone with a trace length smaller than 5 km (M_w 5.5) or if the target fracture is sub-vertical, returns a higher critical radii value.

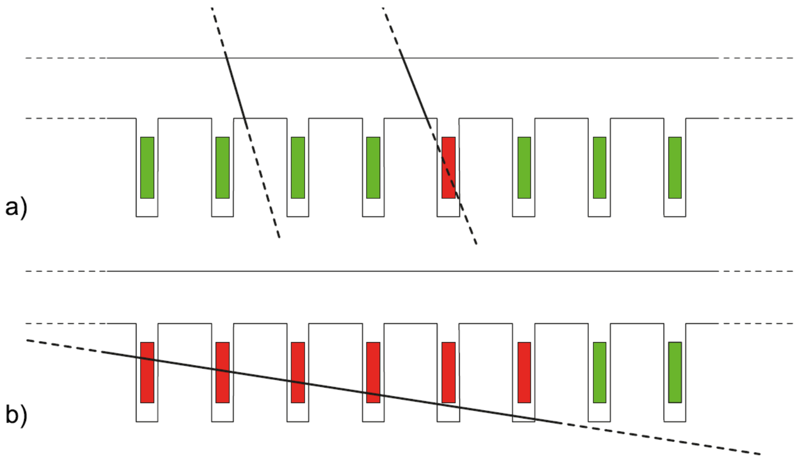

Figure 3: Implications of the EFPC criterion: a) rejection of deposition hole (coloured red) where the extension of a FPI intersects a canister position; and b) rejection of multiple deposition holes where a fracture intersects at least five canister positions. From SKB R-11-14 (p. 19).

Thus, a critical radius of 50 m would appear to be a conservative lower bound for the assumed earthquake magnitudes, slip characteristics, and rock and fracture properties. Conversely, the question of conservatism depends on whether the assumption that fractures at 100 m distance from the source fault will not slip more than twice as much as those at 200 m is valid (see SKB TR-08-11, p. 119). Linear interpolation of the 3DEC modelling results reported in SKB TR-08-11 (pp. 82-83) would suggest this to be a fair assumption. However, it is recognized that the specific case of induced fracture shear displacements 100 m from the source fault was not directly modelled.

Conservatism incorporated into the EFPC is necessitated by the need for a robust and simple method to identify potentially discriminating fractures. As discussed in SKB TR-10-21 (p. 7), the full size of a fracture can rarely, if ever, be measured due to the limited exposure afforded by underground openings and limitations in relying on geological signatures or geophysical techniques (as reviewed in SKB R-06-39). Accordingly, the procedure proposed by SKB to identify discriminating fractures, with respect to mechanical stability and deposition hole approval (SKB R-11-14, p. 50-51), involves the following steps:

1) Detailed mapping of the deposition tunnels will first be used to identify FPI fractures. Tunnel-based radar, seismic and cross-tunnel seismic measurements are suggested as possible means to further detect the presence of large, sub-horizontal fractures below the tunnel floor that might intersect several canister positions.
2) Pilot holes will be drilled in preliminary deposition hole positions selected to avoid locations disqualified based on the FPI criterion. Borehole mapping will be carried out using borehole televiewer logging (SKB R-11-04, p. 85-86), together with the possible use of borehole and cross-hole radar and seismic reflection.
3) Based on the pilot hole results, full deposition holes will be drilled where the EFPC criterion for consecutive holes is satisfied and other acceptable conditions are found. Geological mapping of the borehole wall will be carried out using a methodology that has not yet been determined in detail.

Reference is made to the use of photogrammetry (SKB R-11-04, p. 64). After mapping of the walls of several consecutive deposition holes, the EFPC criterion would be assessed once again for confirmation.

3.2. SKB's plan on hydraulic properties

The EFPC is also proposed as a means to complement inflow observations in terms of identifying hydraulically unfavourable deposition hole positions. Groundwater inflow into the deposition holes, if high enough, could have a large impact on both the loss of bentonite which may potentially lead to advective conditions and on the rate of canister corrosion by sulphide in the groundwater (SKB TR-11-01, p. 764). Thus, the identification of large fractures is also a key requirement to fulfil SKB's Design Premises regarding the barrier function (hydraulic properties) of the rock, together with its interactions with the engineered barriers (Table 3).

As noted in Table 3, SKB suggests that many high flow positions will likely be screened out by the application of the EFPC. This is based on the frequently observed correlation between fracture size and transmissivity such that application of the EFPC would reduce the number of high Darcy flux deposition holes significantly (SKB TR-11-01, p. 765). Additional inflow monitoring would then be carried out to ensure conformance to the Design Premises. SKB projects that only a few additional deposition holes, up to 6% in the most extreme case, will be rejected due to measured inflows higher than 0.1 ℓ/s (Figure 4; SKB TR-11-01, p. 158).

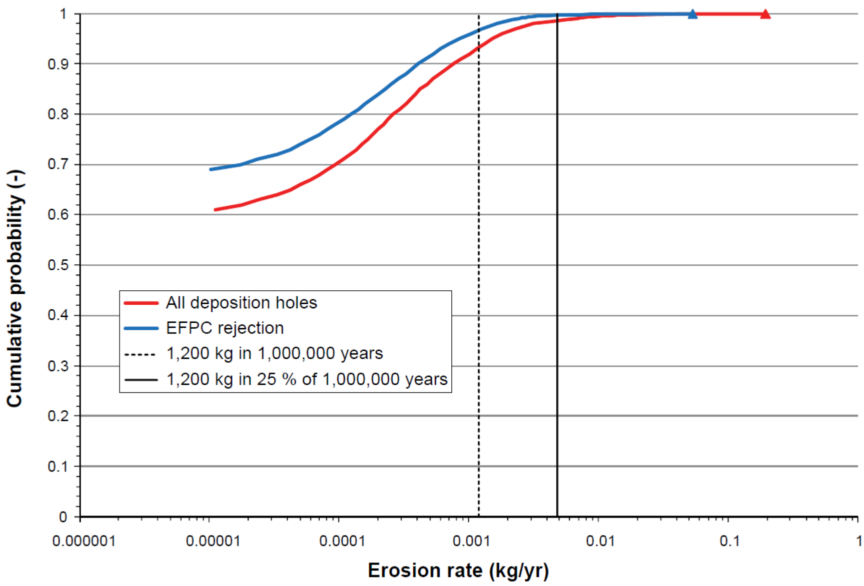

Figure 4: Projected effectiveness of the EFPC at screening out large fractures with the potential to produce advective conditions in the buffer. The erosion rates required to achieve advective conditions in a deposition hole are given as vertical lines, for dilute conditions all the time (dashed line) and 25% of the time (solid line). From SKB TR-11-01 (p. 402).

Table 3: Characterisation plan for meeting Design Premises related to EFPC and deposition hole acceptance/rejection with respect to hydraulic properties (SKB R-11-14).

Design Premise	Role of Detailed Characterisation	Status and Development Need for Methods
<u>Hydraulic Properties</u>:		
Fractures intersecting the deposition holes should have sufficiently low connected transmissivity. (This Design Premise is linked with the related Design Premise: *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 present knowledge, that the total volume of water flowing into an accepted deposition hole must be less than 150 m^3*).	SKB suggests that most deposition positions intersecting water conducting fractures will be screened out by the application of the EFPC (SKB TR-10-18, p. 37). SKB further points to the Design and Construction report (SKB TR-10-18) to indicate that these criteria would be fulfilled if the inflow into the deposition hole is less than about 0.1 ℓ/min*. This is a measurable quantity that can be used to assess acceptability. Hydraulic testing combined with initial inflow measurements in pilot holes are planned to establish specific maximum inflow values. This will permit a preliminary assessment of fulfilment of the design requirement before drilling of the deposition hole. Final verification can be made just before the bentonite and canister are to be placed in the deposition hole.	SKB judges that inflow measurements, whether done manually or recorded using instruments, will be able to be carried out using known and available methods and therefore require no special development initiatives, aside from modification of measurement instruments for the task at hand. Hydraulic tests, including interference tests between pilot holes in deposition holes, can be carried out using known technology. The methodology for evaluation and modelling to verify fulfilment of the design premise will be developed as a part of the integrated modelling methodology on the tunnel scale.

* Note that references to the threshold value of 0.1 ℓ/min in SKB TR-10-18 only appears in the context of maximum inflows permitted into the deposition tunnels and its potential impact on backfill installation.

Consideration is also given with respect to the measured inflow criteria that the deposition hole wall conditions will be disturbed by skin effects and grouting. It is suggested that these disturbances may be partly overcome by requiring that deposition holes intersected by fractures capable of providing inflows above a certain value are to be avoided, not just those directly measured (SKB TR-11-01, p. 765). This suggests that the hydraulic properties of the fractures intersecting the borehole should be tested in the pilot hole prior to drilling the full size deposition hole, thereby avoiding skin effects, and that deposition holes intersected by fractures showing visible grout should also be rejected, since the presence of grout suggests that the fracture was quite transmissive before grouting.

Accordingly, the procedure proposed by SKB to identify discriminating fractures with the potential for producing unacceptably high inflows, includes the following steps (SKB R-11-14, p. 49-51) in addition to those previously listed with regards to mechanical stability:

1) Prior to excavation of the deposition tunnels, pilot holes will be drilled to probe for water-conducting features. If detected, hydraulic cross-hole

measurements (interference tests) will be performed between adjacent deposition tunnel pilot holes. Pilot holes intersecting conductive fractures will also be equipped with packers so that hydraulic responses from the drilling of subsequent pilot holes can be detected to identify the extent of hydraulic connectivity between deposition tunnels.

2) During excavation of the deposition tunnels, total water inflows will be measured as soon as possible after tunnelling. This will be done using water flow weirs positioned at the tunnel mouth (SKB R-11-14, p. 102). It is also noted that point measurements of water inflows are required; details are not provided. It is noted elsewhere that the development of methods for measuring small seepage in tunnels is planned (SKB R-11-14, p. 65).

3) Pilot holes drilled in acceptable deposition hole positions will be logged for water inflows and possibly subjected to hydraulic interference tests to identify and characterise large fractures that may intersect several pilot holes.

4) With drilling of the full deposition holes, water inflows will be measured and compared to the relevant criteria set out in the Design Premises. Special research and development initiatives, in cooperation with Posiva, are referred to as being in the planning stage to develop methods for measuring small inflows in the pilot holes and full-faced deposition holes (SKB R-11-14, p. 65).

3.3. Issues and weaknesses identified during SSM's Initial Review Phase

Potential issues and weakness identified during SSM's Initial Review Phase related to the EFPC include (Eberhardt and Diederichs, 2012, SSM Technical Note 2012:39):

- The likelihood of encountering sub-horizontal brittle fracture zones at the repository depth does not appear to be considered in the qualitative risk analysis. The resolution of proposed detection methods (seismic reflection, single-hole interpretations) relative to the minimum size of a sub-horizontal deformation zone they can detect could not be found in SKB's reports.
- The EFPC criteria only allows for fracture extent as mapped, not for the possibility that non-persistent fractures in near proximity to one another may propagate/coalesce during subsequent construction/operation activities in response to further mechanical and thermal induced stress changes. This may result in a non-discriminating fracture evolving after canister placement to a condition where borehole rejection would be warranted based on the EFPC.
- Similarly, there does not appear to be a deposition hole rejection criterion that considers a non-discriminating fracture which meets the acceptance criteria, but during subsequent construction/operations connects with EDZ/spalling along the Deposition Tunnel floor resulting in connectivity being established with a water bearing fracture leading to excessive water inflows. Continuous EDZ should be treated jointly with the fracture intersection scenarios described in the EFPC with respect to Design Premises related to deposition hole inflows.

- Further review is required on the effectiveness and reliability of seismic and radar reflection (or other geophysical techniques) for detecting discriminating fractures in a construction/operations environment.
- The long-term function, if any, that grouting is expected to play could not be found.
- 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. the presence of adverse geology/fractures in the farther reaches of the repository). It is not clear what the implications would be (in terms of project risk) if the rejection ratio of deposition holes increased after the options for adapting were significantly more limited. For example, inspection of the geological data reported in SKB R-07-45 indicates that the western margin of the target area borders a major tectonic feature that appears to be a splay(s) of the Eckarfjärden regional deformation zone (see ZFMNW1200 and ZFMWNW0123 in Figure 5). It is very likely that the rock mass conditions encountered in this part of the repository will be more tectonically disturbed, and therefore contain significantly more discriminating fractures than the rock mass encountered in the central area. Implicitly assuming that the conditions will be homogenous throughout each rock or fracture domain introduces considerable risk.

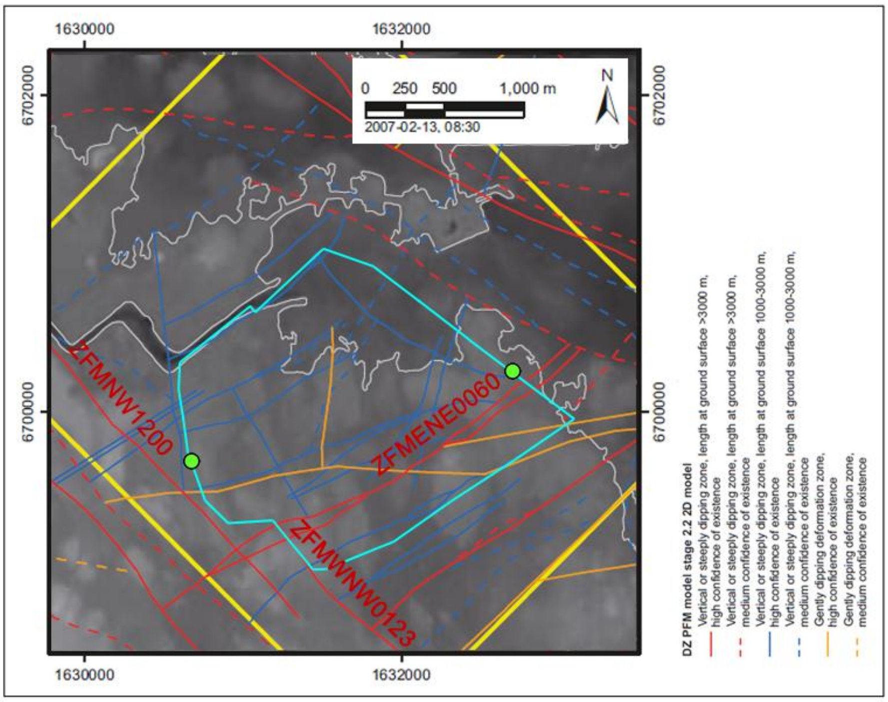

Figure 5: Surface intersection of major deformation zones along western margin of repository target area. Modified from SKB R-07-45 (p. 166).

3.4. The Consultants’ detailed review and findings during SSM’s Main Review Phase

On EFPC and Detection of Large Fractures

- SKB suggests that with respect to the “best available technique (BAT)”, there is room to improve the EFPC in future as it unnecessarily implies rejection of many holes only intersected by short fractures (SKB TR-11-01, p. 46). This is correct, the EFPC is very conservative. For example, the FPI component of the EFPC could exclude deposition hole positions intersected by fractures as small as 3 m in radius compared to the critical radius of 62.5 m, which represents the minimum fracture size required for slip to exceed the 5 cm threshold specified by the Design Premise regarding mechanical stability. However the FPI component of the EFPC, implemented through visual inspection and fracture mapping of the deposition tunnel, is very robust. Reference is made to on-going work with Posiva to find other means to identify large discriminating fractures to increase the efficiency of the criterion.
- One of these studies, as described in SKB R-11-14 (p. 73), suggests development work to identify which fracture properties can be detected by a given investigation method, to then be used for early identification and characterisation of large fractures. Recently, Posiva released a working report on the use of geological data from pilot hoes for predicting FPI fractures (Joutsen, 2012). The study compared 39 FPIs mapped in the Onkalo tunnel to those logged in the pilot holes. The results indicated that there were certain geological properties common to the fractures in the pilot hole and those mapped as FPI fractures, including their dip and dip direction, surface roughness/profile, infilling minerals, joint alteration, and thickness of infilling material. However, these were also found to vary adding uncertainty to the FPI predictions and making it impossible to predict with any certainty whether a fracture intersected in a pilot hole is or is not a FPI. Joutsen (2012) concludes that a fracture with strong FPI indications due to its nature in a pilot hole does not necessarily mean that it truly is a FPI and vice versa.
- The second part of the EFPC stipulates that a fracture or deformation zone intersecting five or more canister positions would result in these positions being rejected. Given the lack of success in identifying large discriminating fractures using pilot hole drilling (Joutsen, 2012), implementation would require that all deposition holes in a deposition tunnel be drilled before it can be decided whether they meet this criteria or not. It is therefore conceivable that an entire deposition tunnel complete with deposition holes, could be rejected after they have been excavated if a sub-horizontal discriminating fracture is encountered below the tunnel floor. Ground probing radar could potentially help in the detection of the fracture before the effort and cost of excavating the deposition holes is committed (the deposition tunnel already being constructed and presumably still needing to be backfilled). Contingency plans should be expressed for scenarios that may result in a large number of concentrated deposition hole positions being rejected. Accordingly, some of the uncertainties to be managed by the Observational Method, which plays a central role in managing uncertainty during construction (SKB TR-10-18, p. 28), will not be resolved until after construction and operations are well underway (e.g. the presence of adverse geology/fractures in the farther reaches of the repository). It is not clear what the implications would be (in terms of

project risk) if the rejection ratio of deposition holes increased after the options for adapting are significantly more limited based on the sequence of building out the repository from the central area outwards. Is it likely that the rock mass conditions on the periphery of the target volume will be less or more adverse if they coincide with geological boundaries or tectonic margins?

- Several configurations are recognised by SKB where large fractures could possibly escape detection using the EFPC, including where discriminating fractures are located near the edge of a tunnel (avoiding the FPI) and have orientations that maybe only intersect two or three canister positions, or where large discriminating fractures intersect the deposition holes close to the fracture tip (SKB TR-10-21, p. 13). It could be argued that the amount of slip varies along a fracture, decreasing towards the fracture tips. SKB TR-10-21 (p. 54) suggests that even if a deposition hole is intersected by a critical fracture, the integrity of the canister will not be jeopardized as long as the intersection point is not too close to the central part of the fracture where the slip is largest. It is highly unlikely such an assessment could be made *a priori*. SKB refer to Kim and Sanderson's (2005) work in acknowledging that observations of maximum slip are rarely positioned at the centre of earthquakes. The criterion also does not consider the presence of small intact rock bridges between non-discriminating fractures that may coalesce into a larger fracture due to the redistribution of stresses during construction, operations, thermal phase or during the potential earthquake event itself. Kim and Sanderson (2005) note that maximum fault lengths are often underestimated due to a failure to resolve low-displacement dips and damage zones between interacting fracture segments. Further investigations may be warranted to determine the importance of intact rock bridges in the context of critical radius and maximum slip as a function of fracture shear strength, for which the rock bridges represent cohesive elements along the overall fracture length.

<u>On Geophysical Methods and Detection of Large Fractures</u>

- In its description of the application of the EFPC (e.g. SKB R-11-14, p. 44), SKB refers to the use of radar and seismic reflection in different configurations relative to the different stages in the deposition tunnel and borehole construction sequence. Reference to their use is sometimes ambiguous, inferring a sense of uncertainty in their reliability as well as to whether they will actually be used or not. First, radar and seismic reflection are to be performed in the main tunnel from the walls facing a planned deposition area. These "can" detect large fractures with "suitable" orientations. Next, borehole radar and seismic reflection are proposed for the pilot holes drilled for the deposition tunnels. From these it "should be possible" to determine the orientation of suitably oriented fractures. During deposition tunnel construction, radar and seismic reflection "can again be used"; the use of cross-hole tomography is included as this "could" reveal additional properties. These are then repeated for the deposition hole pilot holes and construction. SKB notes that the basic methods are established, but that development work is still being pursued (e.g. SKB R-11-14, p. 49, 64, 73).

- The ambiguity and question of reliability in SKB's plans to use geophysical techniques to detect large fractures, mirrors their limited use in common practice in rock engineering and underground construction projects. Geophysical methods have long held the promise of imaging large volumes of rock to detect large fractures that may otherwise go undetected behind the boundaries of an excavation or borehole. Advantages include being non-invasive and capable of evaluating large volumes of the subsurface rapidly. However, they also have their limitations. Key considerations with respect to fracture detection include: i) fractures must be suitably orientated relative to the source and receiver positions (i.e., fractures may go undetected if not suitably orientated); ii) the detection resolution and depth of penetration are usually inversely related (i.e., the higher frequency energy transmitted into the ground using radar compared to seismic results in a higher resolution but more limited penetration depth); iii) fracture detection is dependent on the degree of anisotropy they impose on the physical properties of the rock (i.e., dry fractures are less visible than fluid filled fractures, as are tight/closed fractures under high confining stresses relative to open fractures); and iv) fracture detection must be interpreted, introducing a high degree of subjectivity in both the extensive processing of the raw data required (i.e., inversion routines applied) and the identification and delineation of reflectors (i.e., fractures) in the processed output.

- In a review of feature detection and confirmation methodologies, Karasaki et al. (2007) examined the experiences from several underground laboratories and repository programme sites around the world: Yucca Mountain (USA), Mizunami and Horonobe (Japan), AECL-URL (Canada), Äspö (Sweden) and Olkiluoto (Finland). The description of the different experiences at these sites suggests that a combination of geophysical techniques is needed. Seismic reflection surveys were favoured to detect major fractures, Ground Penetrating Radar (GPR) was cited for locating low dipping fractures, and borehole and cross-hole seismic and radar were cited for detecting the location, continuity and geometry of fractures and features away from/between boreholes. Thus, a number of repository programmes are considering the same geophysical techniques as SKB, but similar language is used with respect to their applicability, reliability and confidence. For example, studies at the Grimsel Laboratory in Switzerland conclude that GPR techniques are "adequate" for mapping water filled fractures in crystalline rock sub-parallel to the measurement surface (Carbonell et al., 2006); dry fractures are significantly less visible as the contrast in the dielectric property between the fractures and the rock matrix decreases. Similar sensitivities to water-filled versus dry fractures also apply to seismic reflection. Certainty in knowing whether fractures are water filled or dry *a priori* may be determinable based on the local hydrogeology. However, this may become less certain for sparsely connected fracture networks, or where local draining of fractures occurs during construction. Likewise, the presence of saline water in fractures limits the effectiveness of radar due to the significant attenuation caused by the high electrical conductivity of saline water (Day-Lewis et al., 2004). As noted in R-11-14 (p. 48), this increased attenuation serves to reduce the penetrating power of radar, making radar measurements less reliable for zones at great distances from the tunnel where saturated by saline groundwater. Thus, radar and seismic reflection methods may be capable of detecting water filled discriminating fractures, however the question becomes one of fracture/fluid characteristics and whether an unacceptable number of discriminating fractures will go undetected due to one of the limiting factors discussed above. Where a FPI is identified through tunnel mapping and radar/seismic reflection is used to determine whether its length qualifies it as a discriminating fracture or not (larger or smaller than twice the critical radius), the question remains whether the full length of the fracture can be reliably resolved, or again, due to the limitations previously stated (see also those in the previous comment), whether only part of the fracture length might be detected misrepresenting its total length.

- SKB's own experiences with borehole radar are briefly described in SKB R-11-14 (p. 86-88). Reference is made to the RAMAC borehole radar system, which was developed in conjunction with the Stripa project and is described in the pioneering work of Sandberg et al. (1991). SKB has considerable experience with the RAMAC system having logged a large number of investigation boreholes in combination with borehole televiewer logging. SKB quotes the range of the RAMAC system to be up to several tens of metres in crystalline rock. This was seen to reduce to 20-25 m where the salinity was 10% (SKB TR-05-11, p. 110). The site description of the groundwater composition (SKB TR-08-05, p. 419), states that the water composition is indicative of a brackish marine water with chloride concentrations in the range 2,000 to 6,000 mg/ℓ below 200 m depth. This would seem to suggest that radar techniques will not be able to resolve the full length of FPI fractures intersecting boreholes if these fractures are filled with saline water.

- Such limitations appear to be reflected in SKB's repeated reference to on-going work with Posiva in the further development of radar and seismic methods to identify large discriminating fractures (e.g. SKB R-11-14, p. 73). Several working reports have since been published by Posiva on the results from these trial tests:

  Seismic Reflection (Sireni, 2011): A review of observed seismic reflections for 14 intersections involving brittle faults, Tunnel Cross-cutting Fractures (TCF) and lithological contacts, demonstrated that seismic reflection can be used to detect such features. However, not all features were successfully detected. Of the 14 known features, a reflector could be interpreted with reasonable reliability for nine of these. Detectability of the tunnel cross-cutting fractures was reported to be poor, with none of the three TCFs surveyed in the study having a clear reflection. Water conductivity was detected five times in the clear reflector cases. Mineralogy explains three of the cases. The study concludes that no guarantees exist that a seismic response will be received, and that interpretation is difficult and uncertainties exist.

  GPR (Heikkinen and Kantia, 2011): A review of observed GPR reflections, and assessment of visibility of large fractures, demonstrated that GPR can detect reflections from cleaned and dry rock floors and walls. The use of higher frequency antennae allowed for higher resolutions but more limited penetration depths (8-12 m for a 270 MHz antenna, 20-40 m for 1 100 MHz antenna). The lower frequency antenna also had the trade-off of higher interference due to a weaker coupling with the rock surface caused by the large antenna. The study concludes that GPR measurements provided detailed information on reflecting bodies 10-20 m below the tunnel floor or behind the wall, with the best results being limited to 7-12 m depth. Depth penetration is stated to be 20 m at best. Specifics aren't provided whether this applies to water saturated fractures or if the water was saline, with the description of the GPR survey simply stating that fracture filling (water, clay, sulphide, graphite) is causing good contrast (Heikkinen and Kantia 2011, p. 13). The use of two antennae frequencies in any future surveys is recommended to provide more reliability in the results. The final conclusion states:

GPR may not detect all types of fractures, so the final judgment is left after drilling and core mapping of the pilot hole, and mapping of the disposal hole. The GPR method alone cannot be used for rejection of disposal hole locations without checking the origin of the reflector.

Borehole Radar (Döse and Gustafsson, 2011): A review of observed borehole radar reflections demonstrated that 50% of the reflectors could be explained by fractures intersecting the pilot hole, but only 10% could be explained by tunnel cross-cutting fractures. A penetration depth of 10 m is reported (using a 250 MHz antenna). The study reveals the great difficulty of finding TCFs using pilot hole radar reflectors: only 20-30% of the TCFs were predicted (when aided by pilot hole mapping data). Difficulties were identified in detecting TCFs with a low angle (0°-20°) to the tunnel and pilot hole, as well as those at a high angle (70°-90°); the preferable intersection angle was 30° to 60° for TCFs to be visible in the radargram. Foliation or banding in the rock was also seen to be an obstacle. No details were provided as to the resolvable lengths of those fractures detected. The study concludes that borehole radar should not be dismissed but that one must be very careful in interpreting radar data.

- Details regarding the seismic and radar reflection probes to be used, relating their probe lengths to the coverage they can provide relative to the borehole bottom could not be found in any top level documents (SKB R-11-14, TR-11-01, etc.). Details regarding the borehole radar RAMAC system used in the investigation boreholes drilled would seem to suggest that the bottom 3-5 m of the borehole cannot be logged depending on the frequency of antenna used (which involves different antenna separations and therefore probe lengths). For example, data reports for KFM01C, drilled into the centre of the target volume, reports a borehole length of 447 m (SKB P-06-133, p. 32), but a radar logging interval of 1.5 to 443 m for a 250 MHz antenna (2.4 m antenna separation), and 2.6 to 440 m for a 100 MHz antenna (3.9 m antenna separation); see SKB P-06-98 (p. 14). Given the 8 m depth of the deposition hole, it may be questioned whether the technique would be able to resolve discriminating fractures relative to the bottom half of the pilot hole. This would of course depend in part on the dip angle of the reflecting fracture. SKB R-11-14 (p. 64) simply states that some existing probes may be too long for use in deposition holes and may need to be modified.
- Similar to the comment above, SKB R-11-14 (p. 64) addresses issues relating to the use of photogrammetry to identify and map fractures intersecting the deposition holes by stating “scaling down from tunnel mapping to deposition hole requires considerable development in order for photogrammetry to be used”. This would seem feasible as there are some reported successes in using photogrammetry in small shafts with dimensions smaller than the deposition hole diameters, albeit with limited accuracy – on the order of several millimetres (e.g. Böhmová et al., 2010). Given the importance of identifying fractures that intersect the deposition holes to the application of the EFPC criteria, it is essential that a method for doing so is established. Downhole visual geological inspections have been routinely carried out in boreholes as small as 1 m in diameter (Scullin, 1994), and such techniques were successfully employed by SKB in the trial mapping of a deposition hole performed from a cage (SKB IPR-03-28 and TR-07-01). Nevertheless, development of a remote sensing technique, such as photogrammetry and laser scanning (see SKB IPR-08-10), to carry out

this important task would seem vital for ensuring consistency, objectivity, a detailed data record, and safety, avoiding placing workers in a confined space environment.

- Projecting ahead to the coming decades, it is certain that computing power and inversion algorithms for processing geophysical data will continue to improve. However, this will still not counter limitations related to the fact that the measurements being made only indirectly identify the presence of a large fracture; verification would still be required. Issues of measurement noise, attenuation and subjectivity in the interpretation of results will likely continue. In fact, the Authors suggest that the necessary advances in the reliability of seismic and radar methods in the years to come, and robustness of the data interpretations, will not come from improved data processing (an area where much research and development is currently being focused by practitioners) but from the deployment of more sources and receivers. Denser data sets are required. Cross-hole tomography between two boreholes only images a 2-D plane. What is needed is to utilize the full 3-D geometry of the repository with its different tunnels and deposition holes providing different sensing directions relative to the different orientations and spatial characteristics of any large fractures present.

<u>On EFPC and Deposition Hole Inflows</u>

- Application of EFPC is also important for protection against buffer erosion and corrosion failures. It is likely that a subset of critical fractures identified by the EFPC are also hydraulically active, display previous shear displacements or have large apertures/thicknesses to ease identification if only a small portions are exposed (SKB TR-10-21, p. 85). However, SKB state that a reference method for the selection of deposition hole positions with acceptable inflows still needs to be developed (SKB TR-10-18, p. 51). The reference method continues by acknowledging that SKB also needs to develop a procedure for verifying that the inflow into a deposition hole conforms to the Design Premise. The framework programme for detailed characterisation describes this as a special initiative to develop methods for measuring small seepage in pilot holes for deposition holes and finished full-face deposition holes (SKB R-11-14, p. 65). Reference is also made to developing similar methods for measuring small inflows in the deposition tunnels. During excavation of the deposition tunnels, total water inflows will be measured as soon as possible after tunnelling. This will be done using water flow weirs positioned at the tunnel mouth (SKB R-11-14, p. 102). It is also noted that point measurements of water inflows are required; this is stated as work currently being pursued in cooperation with Posiva.

- Any monitoring and assessment of deposition tunnel/hole inflows need to also consider the potential for changing flow conditions. Performance assurance measures should be developed to ensure that deposition holes initially assessed as being acceptable do not afterwards experience high inflows due to a change in the connectivity of the fractures intersecting the deposition hole, for example through the development of a high permeability EDZ/spalling zone in the deposition tunnel floor that serves as a conduit.

4. Performance of Geological and Geophysical Methods: EDZ, CDZ and Spalling

4.1. SKB's plan on geological and geophysical methods

The term EDZ (or Excavation Damaged Zone) according to SKB refers to the zone of damaged wall rock around a tunnel or deposition hole that can be caused by blasting or mechanical rock excavation and unfavourable rock stress conditions. The Authors note that this is a very broad definition and is problematic for the development of monitoring and control strategies. SKB's EDZ management is primarily focussed on the selection of which rock excavation technique will be used. However, overstressing also contributes to EDZ independent of excavation method. The Authors' earlier review (SSM Technical Note 2012:39) had suggested a separation of the Construction Damage Zone (CDZ), related to blasting and/or mechanical excavation, from that of stress-induced EDZ. Within the latter, spalling is an important mechanism as is the disturbance and dilation of existing geological fractures.

Related Design Premises (Table 4) include limits on the hydraulic (or diffusive) connectivity of EDZ in the deposition tunnels and deposition holes (SKB R-11-14, p. 74). Although the focus of this review is on the deposition holes, it should also be noted that there is a limit on the maximum permeability allowed in the EDZ surrounding the ramp, shafts and main/transport tunnels below the top seal (SKB TR-11-01, p. 833):

> *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.*

With respect to stress magnitude in the horizontal direction, SKB acknowledges that uncertainties remain concerning the stress magnitudes at repository depth at Forsmark (SKB R-11-14, p. 43). Uncertainties regarding the stress field orientation are considered to be smaller. Stress analyses reported in SKB R-08-116 are cited as showing that if the deposition tunnels are oriented within ±30° of the maximum horizontal stress direction, the risk of spalling in the deposition holes will be minimal for the most probable rock stress magnitudes. This is pointed to as being a controlling principle in arriving at the repository's current reference design (SKB R-11-14, p. 43). According to SKB R-11-14 (p. 46, 49), it is assumed that some form of supplementary characterisation of the stress field and follow-up measurement of the properties of the EDZ will be carried out, but the methodology for this has not yet been determined or established. SKB states that both the determinations of the magnitudes of the horizontal stresses, as well as a more precise determination of their orientations is a complex task that will require a combination of different measurement methods and observation of possible overloading in tunnels (SKB R-11-14, p. 43).

Table 4: Characterisation plan for meeting Design Premises related to EDZ and deposition hole acceptance/rejection (SKB R-11-14).

Design Premise	Role of Detailed Characterisation	Status and Development Need for Methods
Deposition Holes:		
Before canister emplacement, the connected effective transmissivity, integrated along the full length of the deposition hole wall and as averaged around the hole, must be less than 10^{-10} m^2/s. (Elevated transmissivity outside the borehole wall can result from the development of a mechanically formed excavation-damaged zone or due to stress redistribution).	SKB acknowledges that it is not possible to carry out direct measurement of flow along the deposition hole wall routinely. Verification will instead be based on the development of a reference method for drilling of the deposition holes. The rock stress situation will be further investigated with a focus on repository depth, which means that the orientation of the deposition tunnels can be established with greater certainty. It is foreseen that some form of indirect verification by means of follow-up measurements of the mechanical properties of the deposition hole walls will be carried out during their preparation. High-frequency seismic or radar technology is suggested, but a measurement programme has not yet been defined.	SKB indicates that a methodology for the follow-up measurements of the properties of the deposition hole wall remains to be developed. Development of these methods is cited as being pursued in part in cooperation with Posiva in Finland.
Deposition Tunnels:		
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 deposition tunnel and averaged across the tunnel floor, higher than 10^{-8} m^2/s. (This criterion is deemed preliminary and its adequacy subject to verification).	SKB judges that it is not practical, nor necessary, to continuously verify this criterion by direct measurement along the deposition tunnel walls. Instead, verification will be based on the development of a reference method for rock excavation that is verified to fulfil this Design Premise. The rock stress situation will be further investigated to optimally align the orientation of the deposition tunnels. In addition, indirect verification by means of high-frequency seismic or radar is similarly suggested to measure the mechanical properties of the tunnel walls that can cause elevated transmissivity. Such verification can be done continuously along the tunnel or on randomly selected tunnel sections.	SKB indicates that a methodology for the follow-up measurements of the properties of the deposition tunnel walls remains to be developed. Development of these methods is cited as being pursued in part in cooperation with Posiva in Finland.

The implications of the current stress model are shown in the following plot (Figure 6) based on calculations summarized in SKB TR-10-18. The “unlikely maximum” values are obtained for a tunnel aligned parallel to the maximum stress (optimum orientation) while in the “most likely” scenario the tunnels are at 30° to the maximum. Not addressed, however, is the issue of tunnel construction in a direction aligned less favourably due to inaccuracies in the stress prediction. Verification is required.

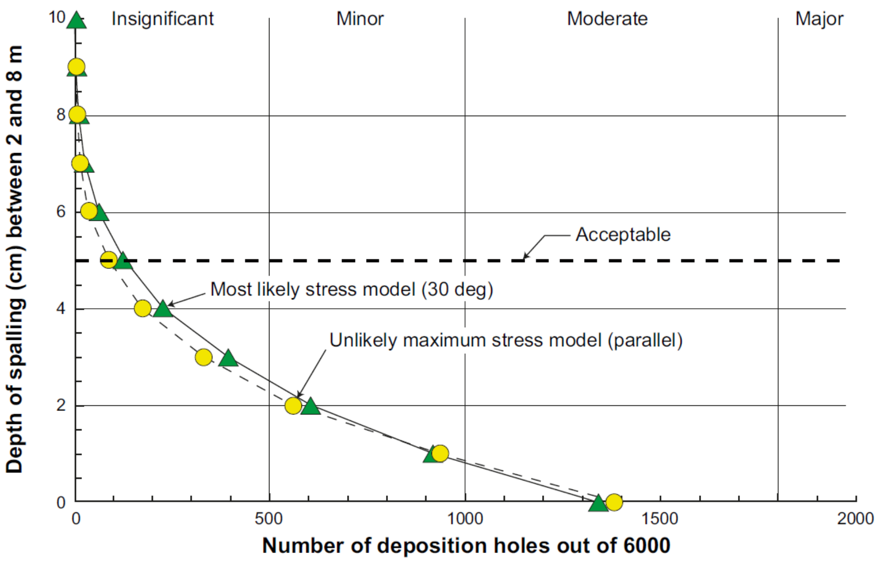

Figure 6: Loss of deposition holes calculated for the most likely and unlikely stress models. From SKB TR-10-18 (p. 38).

SKB R-11-14 (p. 49) describes the planned investigations during and after construction of the deposition tunnel as follows:

1) Pilot holes and relevant updated models will be used to verify that a deposition tunnel offers sufficient canister positions, leading to a positive decision to build the tunnel.
2) During tunnelling, investigations will be conducted in probe holes and tunnel walls mapped according to standard procedures. It is noted that the requirements regarding the EDZ are strictest in the deposition tunnels, especially on the tunnel floor.

SKB notes that since the tunnel geometry and its orientation to the maximum principal stress control where the stress concentrations occur, and thereby the risk of spalling, the deposition tunnels in the current layout have been positioned parallel to the assessed maximum horizontal stress (SKB R-11-14, p. 49). Doing so minimizes the risk of continuous spalling along the deposition tunnels and spalling in the deposition holes.

This assumption will require verification through measurement and back analysis of deformations and EDZ observed during the construction of the preliminary development works. SKB R-11-14 (p. 61) describes the strategy for re-evaluating the *in situ* stress state (a key input for the spalling and EDZ predictions): new data will be collected during the start of construction in the form of tunnel convergence and borehole measurements. With this, a methodology for efficient inverse modelling of the convergence data will be developed. Consideration will also be given to experience from Posiva's extensive analyses of convergence data, overcoring data and data from hydraulic rock stress measurements on different scales (e.g. Hakala et al., 2012).

For the deposition holes, the possible occurrence of spalling will be investigated as they are drilled. SKB R-11-14 (p. 51) describes the process of final approval of deposition holes during construction, build out and documentation of the initial state of the final repository:

> *After investigations in the deposition holes have been finished and models have been updated, a final decision can be made to approve deposition holes for deposition of canisters. At this time, final documentation of deposition tunnels with approved deposition holes can be issued. Excavation of additional deposition tunnels will then continue in this manner in one construction phase after another until all the deposition areas are finished, and finally until the entire repository area is built out and all spent nuclear fuel has been deposited. The final documentation of the underground openings in the entire facility, including any excavation-damaged zones (EDZs) around these openings, comprises the initial state of the final repository for the safety assessment's calculations of long-term safety.*

SKB R-11-14 (p. 64) further discusses the characterisation of the deposition holes including detection and evaluation of EDZ. This will take place in two steps, starting with the drilling of a pilot hole. This will then be followed by geological mapping of the rock type distribution together with the surface structure of the borehole wall with respect to tendencies towards spalling (as well as to investigate the possible occurrence of large fractures as discussed in the previous section). It is then noted that SKB has already begun method development with respect to characterisation of the deposition holes through research carried out at the Äspö HRL and that this will be pursued further.

With respect to EDZ investigation specifically, SKB R-11-14 (p. 64) points to research being conducted in conjunction with Posiva regarding what methods have the best potential for characterising the EDZ. This includes the testing of non-destructive geophysical methods (e.g. high-frequency seismic and radar reflection). Use of Ground Penetration Radar (GPR) is also included in this development work. Reference is made to an experiment being conducted by Posiva, where a combination of GPR and a special form of hydraulic testing has been applied in small-diameter boreholes for characterisation of the EDZ (SKB R-11-14, p. 64). This has the potential to lead to a new strategy for this type of investigation.

Reference to the use of geophysical techniques is again made in SKB's description of the investigation methods and instruments at their disposal, suggesting that geophysical surveys, including seismic refraction, seismic reflection, resistivity and GPR, might be employed for characterisation of the EDZ (SKB R-11-14, p. 100). It is further noted that EDZ will also be characterised hydraulically if necessary to verify that the Design Premises are met. However, this will likely only be done during the development of the reference method for rock excavation of the tunnels and shafts. Such measurements would be difficult to apply as a continuous verification measure during construction since it will likely require a complex measurement setup (SKB R-11-14, p. 100).

In summary, SKB provides the following comments regarding the verification of the design premises with respect to hydraulic conductivity and EDZ (SKB TR-09-22, p. 39-41):

<u>For the deposition holes</u>:

> *Before canister emplacement, the connected effective transmissivity integrated along the full length of the deposition hole wall and as averaged around the hole, must be less than 10^{-10} m^2/s. Conditions for EDZ (due to spalling) was primarily assessed in R-08-108 but need verification in SR-Site.*

SKB describes three main pathways: Q1 = single fracture that intersects a deposition hole; Q2 = EDZ in the floor and below the deposition tunnels; and Q3 = fracture intersecting the deposition tunnel.

As noted above in Section 2.3, the feedback to this Design Premise in SR-Site (SKB TR-11-01, p. 830) suggests that conformity is demonstrated in the Underground Openings Construction Report (SKB TR-10-18). It is further noted that based on the assessment carried out in SR-Site, that spalling may increase the mass transfer (the equivalent flow rate Qeq) for the Q2 path by more than an order of magnitude. It is also important to consider the connection between the spalling and the EDZ around the deposition holes and that in the floor of the deposition tunnel (Q2), as well as the connection between EDZ and single fractures (Q1 or Q3) and vice versa. EDZ and spalling (visible EDZ) could link the deposition tunnels to the deposition holes (bypassing the longitudinal protection of the buffer) or nearby fractures. Deposition tunnel EDZ and/or spalling could also provide a bypass around the backfilling material. Spalling and EDZ development will not be dominant (in terms of local Darcy flux) in the case of advective conditions in the deposition hole or if the canister is damaged by a shearing fracture (SKB TR-11-01, p. 830).

<u>For the deposition tunnels</u>:

> *Excavation induced damage should be limited and not result in a connected effective transmissivity, along a significant part (i.e. at least 20–30 m) the disposal tunnel and averaged across the tunnel floor, higher than 10^{-8} m^2/s. The tunnel contour needs to be smooth enough to allow the required packing and density of the backfill.*

Note this latter part does not appear in the version of the Design Premise that appears in SR-Site. The tunnel contour requirement is sensitive to EDZ. However, reference is made to SR-Can (SKB TR-06-09, p. 550) where analyses presented suggest that even an EDZ with up to one and a half orders of magnitude higher conductivity than the surrounding rock would not imply any major problem with respect to safety. In report SKB TR-10-50, calculations of the annual effective dose are presented for three different assumptions of transmissivity of the EDZ: 10^{-8} (base case), 10^{-7} and 10^{-6} m^2/s. The difference in dose between the base case and the most conservative model with highest transmissivity is a factor 3, corresponding to a dose still below regulatory limit.

<u>For the main tunnels, transport tunnels, access tunnels, shafts and central area and closure</u>:

> *The top sealing has no demands on hydraulic conductivity. Below the location of the top sealing, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones. There is no restriction on the hydraulic conductivity in the central area. The adequacy of these design premises needs to be verified in SR-Site.*

Feedback to this Design Premise in SR-Site (SKB TR-11-01, p. 833) indicates that the Design Premise is deemed adequate. It is noted that additional sensitivity analyses focussing on the hydraulic properties of the access, main and transport tunnels would be required to further relax this criteria.

Note that it is not clear how this verification of conductivity or transmissivity is to be carried out. Direct hydraulic cross-hole testing is an invasive methodology, while geophysical techniques such as those cited can be used to define the EDZ, but would require further research to calibrate them to be used to quantify transmissivity.

4.2. Issues/weaknesses identified during SSM's Initial Review Phase

Potential issues and weakness of SKB’s plan identified during SSM’s Initial Review Phase related to EDZ, CDZ and spalling include (SSM Technical Note 2012:39):

- The stress field used for the EDZ and spalling assessments appears to contain several inconsistencies, including a change in trend of the maximum horizontal stress at 400 m depth (decreasing gradient) without a similar change in the minimum horizontal stress. It was also noted that the stresses measured in boreholes KFK001/DBT1 and KFK003/DBT3, which were used to determine the stress field state, are located outside the target repository volume.
- 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 compiled. The current documentation is complex and leads to the risk of overly confident stress specifications.
- 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.
- Reference is made to the findings of an experiment at the Äspö laboratory used to conclude that EDZ, if it develops, will not be continuous. Review of the experiment details, however, suggests that this conclusion only applies to blast-induced construction damage and not to excavation-induced damage resulting from the redistribution of stresses. In SKB’s experiment, severe stress concentrations would not be expected in the tunnel walls, where the samples were taken, given that the major principal stress at the Äspö laboratory is horizontal. For this stress field orientation, stress-induced damage would be expected to concentrate in the tunnel floor and roof.
- The distinction and separation of construction damage (CDZ) from stress-induced excavation damage (EDZ) is required, 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) involving spalling, extensive slip/opening of existing fractures, interconnection of existing fractures, etc.
- 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 the *in situ* stress.

- It was not clear whether the analysis used to conclude that spalling is unlikely in the deposition tunnels due to their orientation relative to that of the stress field also considered spalling occurring in the tunnel face.
- The 30-35% overbreak limit expressed in the Design Premises for deposition tunnels appears to be excessive or incompatible with the requirement to minimize construction damage. This should be reduced to improve overall quality control. Overbreak in the deposition holes is not included in the deposition hole acceptance/rejection criteria.
- 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 may be warranted.

4.3. The Consultants' detailed review and findings during SSM's Main Review Phase

Uncertainty and Verification:

- The main purpose of verification is to confirm the assumed values and constrain the uncertainties within the geosphere model. From SKB TR-11-01 (p. 45):

  > *The combination of pessimistic handling of uncertainties for which probability distributions could not be determined with the probabilistic handling of quantified uncertainties means that the total risk as determined in the risk summation is claimed to represent an upper bound on risk. Since this upper bound is below the risk limit throughout the one million year assessment period, there are no uncertainties of critical importance to resolve with respect to risk.*

  This statement would seem to imply that pessimistic assumptions have been made throughout the analysis of risk in this case. It could be argued that, while EDZ may not represent a critical risk within the proposed design, it is not convincing that the assumptions regarding EDZ are "pessimistic". As outlined in the SR-Site Data Report (SKB TR-10-52, Sec. 6.4.7), a number of uncertainties exist in the predictive models and analyses related to EDZ development and spalling including:

  1. Uncertainty in stress magnitude
  2. Uncertainty in stress directionality
  3. Variability in the uniaxial compressive strength, UCS, and crack initiation stress, CI (as a function of UCS in this case)
  4. Uncertainty regarding the relationship between CI and UCS
  5. Uncertainty in the influence of moisture/water in reducing CI and/or UCS (more research is required on this effect)
  6. Uncertainty in stiffness variability within the repository footprint

7. Prediction uncertainty for transmissivity in the EDZ
8. Model uncertainty regarding the glacial loading cycles.

  These uncertainties should be resolved to allow more convincing presentation of pessimistic inputs for conservative behavioural analysis. All but the last uncertainty (glacial loading cycles) can be reduced with verification work to be carried out during construction.

- In addition, the assertion of SKB TR-11-01 (p. 46), that:

  > *The selected repository depth is adequate and changing the depth is not deemed to reduce the calculated risk. Furthermore, a shallower depth, e.g. above the 400 m level might increase the risk, since the frequency of water conducting fractures is higher there. Placing the repository some 100 m deeper would probably result in a risk contribution similar to the one obtained from the selected depth, whereas much deeper locations would imply that additional factors, such as very high stress levels, might need to be considered.*

  This is likely correct although the confidence in the details of the current design can be increased with reliable verification measures during development.

- A significant stress measurement campaign is recommended once the repository shaft and access development reaches the operational horizon. High quality overcoring measurements, in spite of all of their difficulties and challenges, still in the opinion of the reviewers represent the best alternative. Multiple measurements in single locations coupled with multiple spatial sampling through the domain should account for both testing-based uncertainties and spatial variability. Tensor averaging of multiple measurements in a single location with spatial analysis of the variations in the local averages, provide noise reduction for a broader comparison of stress variability over the domain. Control of these measurements is much more robust when the sampling distances are small (as compared to deep or remote sampling). The magnitudes in this case (most important for deposition hole array dimensioning) are highly dependent on the measurement of elastic modulus and the minimization of sample damage during the test. Other means of verification for the stress orientations (most important for repository layout) include comparison of performance of drill holes and pilot tunnels in different directions during early development.
- Invasive *in situ* testing techniques involving borehole examination, cross-hole transmissivity testing coupled with geophysical verification and calibration can take place in the early construction stage and will be important for an initial verification of EDZ, validation of the correlation between transmissivity and fractures length as well as calibration of the geophysical techniques to both damage and hydraulic conditions. These techniques are not practical for routine operational verification protocols since an abundance of verification boreholes within the tunnel and canister perimeter is counter to the concept of an undisturbed geological barrier.

<u>Geophysical Methods and Detection of EDZ</u>:

- According to a number of studies performed at Posiva (Silvast and Wiljanen, 2008; Heikkinen et al., 2010; Mustonen et al., 2010), a number of geophysical tools can be used to identify and quantify EDZ extent including:

1. Resistivity using surfaced coupled current electrodes
2. Ground penetrating radar (GPR)
3. Seismic refraction surveys along the excavation wall.

It is interesting to note the comment in SKB R-11-14 (p. 49):

> *Some form of follow-up measurement of the properties of the EDZ is needed, but a methodology for this has not yet been established.*

This is in part due to the fact that significant geophysical development at Posiva post-dates this and other SKB's reports. An investigation is being conducted in cooperation with Posiva to determine which study methods have the best potential for characterising the EDZ. The main non-destructive investigations for characterisation of the EDZ that are being considered are based on geophysical methods (high-frequency seismic and radar reflection). Use of Ground Penetration Radar (GPR) is also included in the development work. An evaluation is currently under way of an experiment conducted by Posiva, where a combination of GPR and a special form of hydraulic testing has been applied in small-diameter boreholes for characterisation of the EDZ in the POSE niche at Onkalo (SKB R-11-14, p. 64). The results could lead to a new strategy for this type of investigations.

- If water is present within the fractures at the time of the geophysical study then GPR and direct resistivity surveying have a greater chance of successfully delimiting the EDZ. Coupling is an issue for resistivity although this is a practical issue than can be resolved with experimentation. While resistivity is a very promising tool in this regard, resistivity surveying at this scale does require a significant preparation logistics and may not serve well as a routine operational tool.
- Most successful demonstrations of electrical methods for EDZ definition have come from studies in clay shales from the continental European programmes although detection of both air filled and water filled meso-fractures have also been reported (Kruschwitz and Yaramanci, 2004; Suzuki et al., 2004; Lesparre et al., 2013). These methods do not "see" individual fractures but rather a cumulative change in electrical properties due to the increased density of micro/meso fractures. Silvast and Wiljanen (2008) report that:

> *The use of ground coupled 1500 MHz GPR in detecting EDZ proves to be promising. Information from GPR data can be used to distinguish changes in electrical conductivity of bedrock and finding fractures. A possible reason for a change in electrical conductivity is increased moisture or moisture flow in the fracture system possibly caused by disturbances from excavation. This zone can then be interpreted from processed GPR data as the potential EDZ. Multi-channel stepped-frequency 3D-GPR provides similar results as ground coupled 1500 MHz GPR. Data collection with the multi-channel stepped-frequency 3D-GPR system is fast and efficient, but the data analysis requires special processing, skilled personnel, and more time. Fractures can be detected well from both systems. The 3D-GPR data*

presents fractures as more continuous reflectors due to the different measurement geometry.

- GPR is the most practical tool to date as systems have been developed based on similar applications such as masonry quality control, pavement analysis, etc. The difficulties lie in rigorous processing and filtering to obtain accurate data. Heikkinen et al. (2010) provide updated information on the potential of GPR for EDZ detection. Section 3.4 in this report discusses many of the physical issues and challenges with resistivity and GPR in detecting fractures of many scales in dry and wet crystalline rocks. This includes the reduction of penetration range when water is present or when conductive mineralogy is present. There is also an issue of limiting resolution with lower penetrative frequencies. The frequency surveying used for tunnel wall EDZ detection does show promise for detection of EDZ where the depth is limited to less than 1 or 2 m in these conditions. Silvast and Wiljanen (2008) report:

  Air-coupled high frequency GPR antennas are efficient in EDZ analysis. 1 GHz and 2.2 GHz antennas both gave clear data, with the 2.2 GHz data having better resolution. Cross-section ground-coupled GPR measurements demand more time and a bedrock surface without steel reinforced concrete lining.

- Seismic refraction is an effective tool for detecting the transition from damaged to undamaged rock based on density increase, but is logistically challenging as an operational tool. This method again depends on a cumulative change in density and acoustic velocity such that refraction can occur at the boundary of the damaged zone. Cabrera et al. (2001) showed promising but inconclusive success in defining EDZ with useful reliability. This mixed success is likely due to the gradual nature of EDZ dissipation and the lack of a sharp refraction boundary between damaged and undamaged shales.

- As noted in Section 3.4 of this report, seismic reflection is unlikely to detect the contrast between damaged and undamaged rock at the scale of EDZ fractures. Borehole versions of these techniques are available with high resolution but they are accompanied by the issue of invasive drilling (e.g. Bäckström, 2008). They do however have the advantage of coupling with visual borehole scanning techniques or linking techniques within a localized hole. These methods may be appropriate for initial verification studies. The results of the work at Posiva are encouraging and suggest a number of valid and viable tools for this verification work. However, calibration and refinement of the resolution and accuracy of these methods is still required as an on-going development.

5. Performance of Geological and Geophysical Methods: Subordinate Rock Types

5.1. SKB's plan on performance of geological and geophysical methods

The thermal properties of the bedrock represent a key design input in determining the spacing between the deposition holes to ensure that the maximum peak temperature in the buffer does not exceed 100°C. However, the spacings determined do not take spatial variations of the thermal properties into account; it is assumed that the thermal properties are uniform (i.e. average value) everywhere within rock domains RFM029 and RFM045 (SKB TR-11-01, p. 326). Thus, the presence and spatial distribution of subordinate rock types with lower thermal conductive properties (i.e. amphibolites, tonalitic varieties of grandodiorite to tonalite, and vuggy granite) is of concern with respect to the satisfying the Design Premise specifying the maximum temperature to be allowed in the buffer (Table 5).

SKB suggests that an effective way of ensuring that the thermal properties are determined correctly is to combine geological mapping with measurement techniques. SKB R-11-14 presents SKB's detailed characterisation programme referenced in Table 5. The characterisation programme will be implemented in conjunction with construction and will include "routine" investigations and

Table 5: Characterisation plan for meeting Design Premises related to subordinate rock types and deposition hole acceptance/rejection (SKB R-11-14).

Design Premise	Role of Detailed Characterisation	Status and Development Need for Methods
The buffer geometry (e.g. void spaces), the buffer water content and distances between deposition holes should be selected such that the temperature in the buffer is <100°C.	SKB plans to use detailed characterisation to progressively update the thermal models for the deposition areas of the final repository. The data will come mainly from geological mapping of boreholes and underground openings, since the dependence of the thermal properties on rock type is well known. Geophysical logging and laboratory analyses of drill cores will provide complementary information. The updated models will be used to describe the spatial distribution of rock types and thermal conductivities. Subordinate rock types with anomalous thermal properties are of particular interest. Field tests at repository depth on a scale that is relevant for the canister heating can be considered to verify the Design Premise.	SKB suggests that the required detailed characterisation can be mainly carried out using known and available methods. Certain development efforts will be made to improve geophysical methods and field tests. Geological mapping will be done using established SKB methodologies. However, a newly developed mapping system will be put into use (as reported in SKB R-11-14, Sec. 7.3.1-2). Further development of a methodology for interpretation of results and thermal modelling will also be done.

modelling required to obtain sufficient information as a basis for design and construction. Routine investigations and modelling will be used for detailed adaptation of the facility to the properties of the existing bedrock to meet the requirements of the project's Design Premises (SKB R-11-14, p. 32). Routine investigations will follow the same general pattern through the construction process; they will be adapted and modified as new knowledge is gained. The main elements of the routine investigations are provided below:

1) Pilot Hole Drilling and Investigations: Pilot holes will be drilled in deposition areas for all main tunnels, deposition tunnels and shafts; they will be installed as needed in the ramp and central areas. Pilot holes will consist of cored boreholes 200 to 300 m in length.
2) Probe Hole Drilling and Investigations: Probe holes will be drilled to a preliminary length of 20 to 25 m in advance of the respective tunnels. Multiple probe holes will be installed.
3) Tunnel Mapping: This will be performed routinely and continuously in all underground openings and will include geometric documentation, bedrock geological mapping, documentation of water seepage and rock and water quality assessment.
4) Continued Monitoring: This will include installation of measurement equipment for groundwater, rock mechanics and thermal *in situ* and laboratory testing, and precision measurements of opening geometries.

Figure 7 illustrates the general sequence of routine pilot/probe hole drilling and investigations planned by SKB. The precise investigation methods planned as part of the pilot and probe hole drilling have not been established by SKB. SKB will primarily utilize methods and instruments that were employed during the site investigations at Forsmark and Oskarshamn, in the Äspö HRL and SFR.

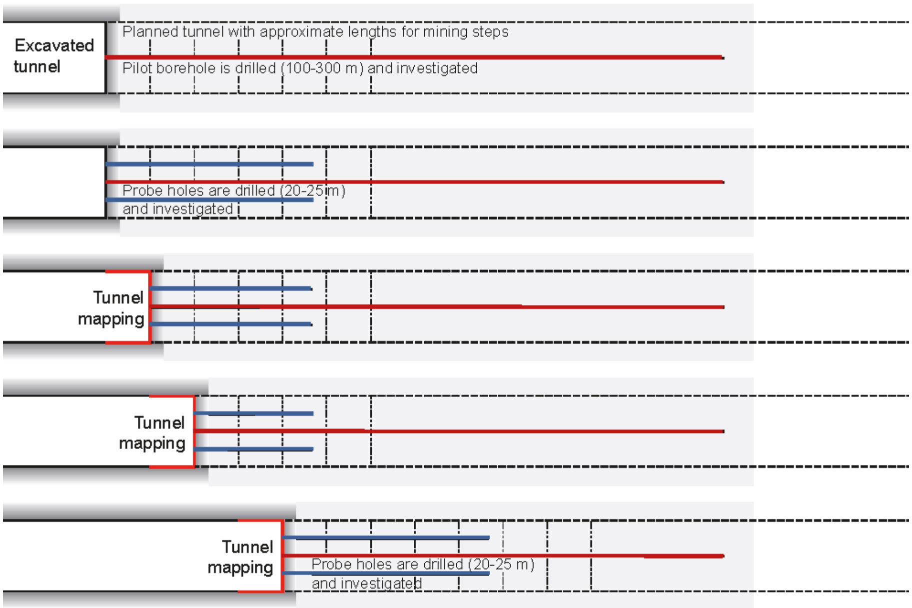

Figure 7: Sequence of pilot hole and probe drilling to be carried out for borehole investigations. From SKB R-11-14 (p. 84).

A generalized work flow for routine investigations during the construction phase was presented in SKB R-11-14 (Figure 8). Based on information provided in this figure, the basic programme investigation methods in pilot holes will include Measurements While Drilling (MWD), Borehole Image Processing System (BIPS), core mapping (Boremap), hydraulic tests, selective water sampling, as well as modelling.

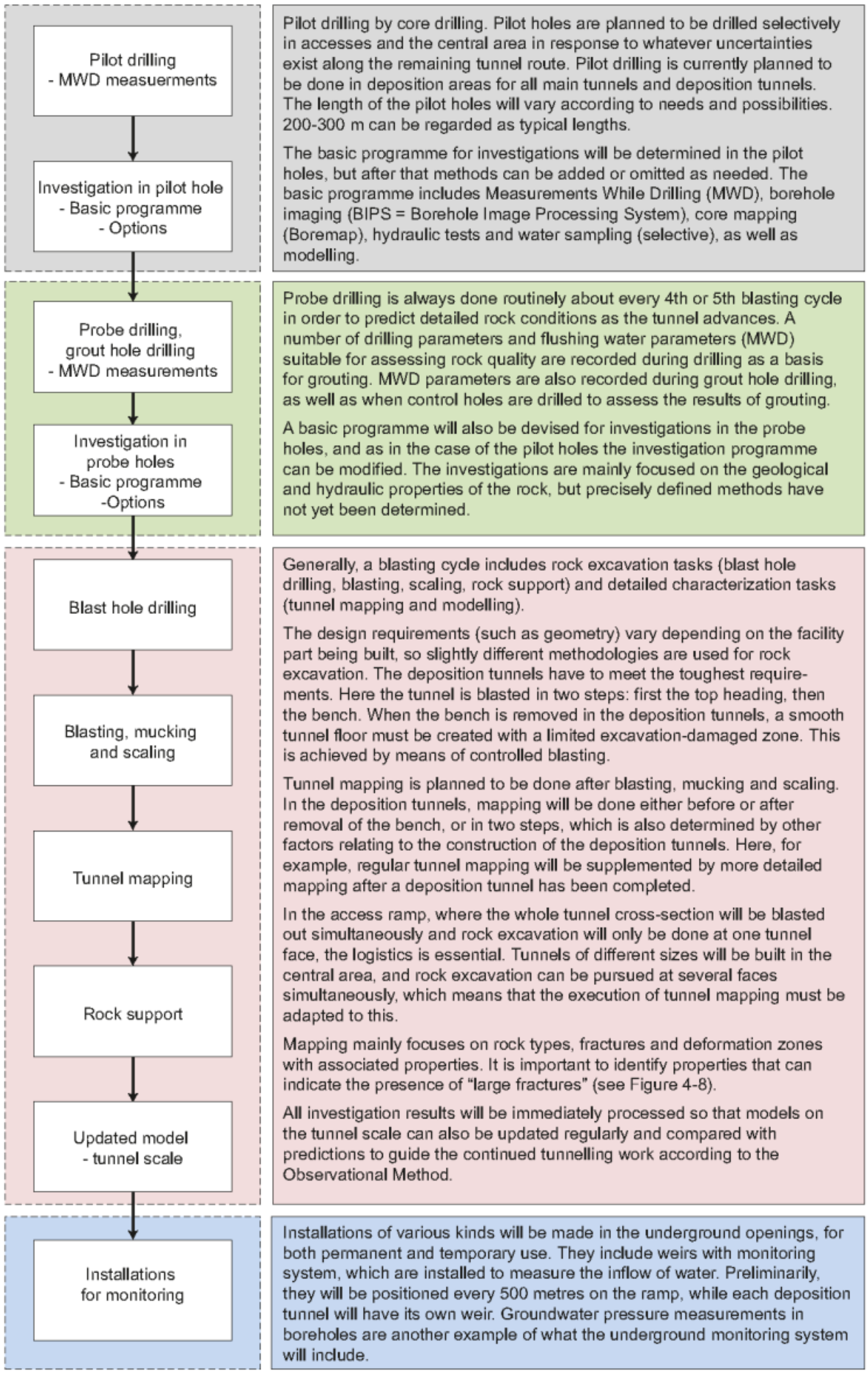

Figure 8: Generalized work flow for rock excavations and comments on possible investigations during construction of the access tunnels, shafts and central area. From SKB R-11-14 (p. 33).

Per SKB R-11-14 (p. 40), SKB plans to initiate the study of large scale variation of thermal properties of the bedrock (subordinate rock types) as part of the detailed characterisation programme performed in conjunction with construction of the central area and continue through deposition hole construction. Borehole and tunnel mapping of encountered/exposed rock types is presented as the primary means of characterizing subordinate rock types and providing information for routine updating of detailed-scale models. If necessary, laboratory analyses of rock samples will be performed as well as yet-to-be developed *in situ* thermal conductivity testing within the deposition tunnels and holes. As of the issue date of SKB R-11-14, SKB was awaiting recommendations from a working group under the International Society of Rock Mechanics (ISRM) tasked with devising a methodology for determination of thermal properties (SKB R-11-14, p 65).

5.2. Issues/weaknesses identified during SSM's Initial Review Phase

Potential issues and weakness identified during SSM's Initial Review Phase related to subordinate rock types include (SSM Technical Note 2012:39):

- The analysis of loss of deposition hole positions does not appear to allow for the occurrence of amphibolite lenses being more frequent than indicated. A methodology should be specified to reliably characterise subordinate rock types (e.g. amphibolites lenses, vuggy granite) in between deposition holes during construction.

5.3. The Consultants' detailed review and findings during SSM's Main Review Phase

- SKB TR-08-05 (p. 109-110) provides the following description regarding subordinate rock types encountered during development of the repository:

  Vuggy granite: Formed by the selective dissolution of quartz, was encountered in boreholes with a thickness of typically a few meters. However, one occurrence in borehole KFM02A was approximately 50 m thick.

  Amphibolite: Although clearly affected by ductile deformation and having metamorphic character, this rock is inferred to have intruded originally. Amphibolite occurs as narrow, dyke-like tabular bodies and irregular inclusions that are elongated in the direction of the mineral stretching lineation. On the basis of the borehole length and the orientation of the contacts of amphibolites encountered in 21 cored boreholes, estimates of thickness indicted that some bodies were more than a few metres thick and, locally (e.g. KFM06C, KFM08D) were tens of meters thick. Most of the encountered amphibolites were inferred to be minor rock occurrences, i.e. thin geological entities. The thicker bodies in boreholes KFM06C and KFM08D occurred in different parts of the fine-grained and partly albitized granitic rocks in the north-eastern part of the target volume.

- Volumetric proportions based on borehole data where subordinate rock types such as amphibolite and tonalitic varieties of grandodiorite to tonlite were encountered ranged from 1 to 11%.

- In a review of albitization and quartz dissolution, Petersson et al. (2012) summarized the geological setting and tectono-thermal evolution and occurrences of alteration by quartz dissolution at the Forsmark site. Excerpts from Petersson et al. (2012) are provided below:

  > *Quartz dissolution has been recorded in more than one third of the cored boreholes, but the alteration type comprises >1% (100 m) of the total borehole length. Individual occurrences are typically a few meters in borehole length, although one occurrence along borehole KFM02A is approximately 55 m (c. −240 to −293 m elevation). Several of the affected intervals in a single occurrence occur close to each other and are separated by a short section of fresh bedrock or less intense alteration. For this reason, the occurrence is envisaged as a complex alteration network.*
  >
  > *Almost 90% of all registered occurrences of quartz dissolution occur within brittle high-strain zones, both the gently dipping fracture zones and the steeply dipping zones that strike ENE–WSW, NNE–SSW and less commonly WNW–ESE. The conspicuous occurrence in KFM02A has been modelled as a narrow, steeply inclined alteration pipe that links two gently dipping fracture zones (SKB R-07-45). Only two occurrences with borehole lengths of 2.2 m and 8.3 m have been observed outside brittle zones in boreholes KFM08A and KFM09A, respectively. In summary, the link to brittle high-strain zones and especially the gently dipping and steeply dipping sets that strike ENE–WSW to NNE–SSW is apparent.*
  >
  > *The quartz dissolution has affected all rock types at Forsmark indiscriminately and contacts with the wall rock are typically sharp or gradational over a few centimeters. All the rocks affected by quartz dissolution at Forsmark have also suffered from moderate to strong hematization (oxidation), giving rise to a brick-red color in the altered rock in strong contrast to that observed in the fresh, unaltered metagranite. The texture of the host rock has been maintained and the vugs or interstices left after the removal of quartz commonly gives rise to a sponge-like appearance in the altered rock. However, the vugs in most occurrences are to a variable extent refilled by hydrothermal assemblages, where quartz, albite, hematite, chlorite and calcite are common. Spatially associated but subordinate rock types initially lacking quartz (e.g. amphibolite) are also strongly altered.*

  Petersson et al. (2012) conclude that the spatial limitations, together with a number of less beneficial mechanical and hydrogeological properties, make evaluation of the thermal characteristics for the episyenites (dissolutioning of quartz leading to vugs) somewhat unnecessary. The typical association with fracture zones which allows some predictability, along with the spatial extent of most episyenites, suggest that these features can be easily handled by standard rock support and possible minor layout changes.

- In addition, review of scientific literature related to geophysical methods that provide indirect determination of bedrock type or thermal conductivity measurements of bedrock on a scale equivalent to that of a planned spent nuclear fuel canister are limited. Determination of thermal conductive properties of bedrock on a scale similar to that of a canister are generally limited to empirical relationships developed based on lab and/or *in situ* measured properties such as density from gamma-gamma logging

(Sundberg et al., 2009) and P-wave velocity (Khandelwal, 2012; Ozkahraman et al., 2004). To date, other nuclear waste disposal facility projects have primarily utilized laboratory testing of cored rock samples to evaluate the thermal conductive properties of encountered bedrock (Karasaki et al., 2007).

Kukkonen et al. (2007) reported on development of a 1.5 m long (76 mm diameter) borehole logging device for determination of rock thermal properties. Although the device was observed to be technically functional, a number of problems were encountered (especially when borehole water inflows were encountered) that required further development and improvement before the equipment could be recommended for use.

- Boreholes (pilot and probe) with investigation and tunnel mapping are currently the primary evaluation methods being used at Posiva in Finland (Paulamäki et al., 2011). Considering this, as well as the limited spatial extent of subordinate rock types anticipated at the Forsmark project site, SKB's basic characterisation programme planned during construction of the deposition panels would be considered the most applicable and currently reliable method for evaluating subordinate rock types. However, the following items are recommended for SKB's consideration:

  1) SKB's characterisation programme should include additional consideration of reported studies for empirical estimation of thermal conductivity of encountered bedrock based on density and P-wave velocities obtained by geophysical borehole logging methods and/or lab testing.

  2) Kriging techniques should be investigated to estimate the rock thermal properties using the properties mapped along the floor of the deposition tunnel and, when available, along pilot holes for the deposition holes, assuming there is a correlation between thermal properties in adjacent positions in the rock.

  3) Future research and development by SKB, Posiva and the ISRM of an *in situ* test methodology for evaluating the thermal properties of bedrock (on a relevant measurement scale of 3 to 5 m) should be closely monitored and supported.

  4) It is not clear how SKB intends to consider thermal properties in the decision making process for location and acceptance of the deposition holes. This should be clearly explained.

6. The Consultants' overall assessment on the performance and resolution of geological mapping and geophysical measurement techniques for the determination of critical properties in and around deposition holes

The following conclusions and recommendations follow from the review findings reported here regarding the Authors' evaluation of the geological and geophysical methods proposed by SKB with respect to their ability, resolution, performance, reliability and robustness to measure the geomechanical parameters critical for determining deposition hole acceptability during repository operation.

1. The conservatism incorporated into the EFPC is necessitated by the need for a robust and simple method to identify potentially discriminating fractures. The detection of the full size of a fracture can rarely, if ever, be measured due to the limited exposure afforded by underground openings and limitations in relying on geological signatures or geophysical techniques.
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. the presence of adverse geology/fractures in the farther reaches of the repository). This may mean that an increase in the rejection ratio of deposition holes could be encountered after the options for adapting are significantly more limited based on the building out of the repository from the central area outwards. The impact of this uncertainty should be considered with those assessed in SKB R-08-116 (Sec. 8); i.e., what are the likelihoods and consequences of the rejection ratio of deposition holes doubling (or tripling) in the second half of repository construction compared to experiences around the central area during the first half of construction?
3. The EFPC criterion does not consider the presence of small intact rock bridges between non-discriminating fractures that may coalesce into a larger fracture due to the redistribution of stresses and thermal strains during construction, operations, thermal phase or during the potential earthquake event itself. Further investigations may be warranted to determine the importance of intact rock bridges in the context of critical radius and maximum slip as a function of fracture shear strength.
4. Recent working reports from Posiva on further development of radar and seismic methods to identify large discriminating fractures indicate that the detectability of tunnel-crosscutting fractures using seismic reflection was poor, that GPR was limited to 7 to 12 m penetration depth and alone cannot be used for rejection of deposition hole positions, and that one must be very careful in interpreting borehole radar data.
5. Although a subset of critical fractures identified by the EFPC would likely be hydraulically active, direct measurement of deposition tunnel and

deposition hole inflows is required to verify conformance with the relevant inflow related Design Premises. Any monitoring and assessment of deposition tunnel/hole inflows need to also consider the potential for changing flow conditions. Performance assurance measures should be developed to ensure that deposition holes initially assessed as being acceptable do not afterwards experience high inflows due to a change in the connectivity of the fractures intersecting the deposition hole, for example through the development of a high permeability EDZ/spalling zone in the deposition tunnel floor that serves as a connecting conduit. SKB should demonstrate that after deposition hole acceptance, the rejection criterion would perform reasonably conservatively after sealing of the tunnel and after closure of the repository. Performance assurance will build trust with the stakeholders.

6. The current assumptions involved in EDZ prediction may not be conservative. This includes the estimation of stress magnitudes, uncertainties in direction, and inherent uncertainties in the measurement of crack initiation threshold and other material parameters. Therefore, verification is required once construction of the repository begins.

7. A systematic stress measurement campaign using high quality overcoring measurements or the LVDT method (Hakala et al., 2012) from development tunnels and shaft stations is required once construction commences. This should be coupled with back analysis studies of drill holes and multidirectional development to confirm stress direction (the most important input into repository layout). Additional measurement from surface is invasive and unlikely to reduce uncertainty.

8. High frequency GPR holds promise as a routine operational tool for systematic tunnel scale EDZ depth determination and spatial distribution assessment. It has significant limitations for detection of more distal fractures. Resistivity surveying can detect EDZ depth with some confidence although the results may be unreliable if the moisture content within the EDZ varies. There are challenges with effective and repeatable data collection due to coupling issues. Seismic refraction can detect EDZ but is not an operationally practical tool. Seismic reflection cannot detect the EDZ/undamaged rock transition. The results of recent studies at Posiva should be brought into a summary document with specific reference to the Forsmark development. This verification strategy should be more specifically defined going forward the construction of the repository.

9. SKB’s basic characterisation programme planned during construction is consistent with methods being utilized on similar nuclear waste disposal projects and are currently the most applicable and reliable method for evaluating subordinate rock types.

10. SKB’s characterisation programme should include additional consideration of reported studies for empirical estimation of thermal conductivity of encountered bedrock based on density and P-wave velocity obtained by geophysical borehole logging methods and/or laboratory testing. The application of interpolation and extrapolation techniques by means of kriging should be also tested if spatial correlation is observed. As currently planned, research and development by the ISRM of an *in situ* test methodology for evaluating the thermal properties of bedrock (on a relevant measurement scale of 3 to 5 meters) should be closely monitored.

7. References

Note that the following references are those cited separate from the review of SKB reports. The SKB reports reviewed and cited in this report are listed in Appendix 1.

Bäckström A., 2008. Äspö Hard Rock Laboratory. DECOVALEX. Validation of the ultrasonic borehole investigation in the TASQ tunnel. SKB IPR-08-05, Swedish Nuclear Fuel and Waste Management Co (SKB).

Böhmová, D., Šeliga, M., Vala, D., 2010. Determination of verticality and straightness of blind shaft using digital photogrammetry. *GeoScience Engineering* 56(2): 59-66.

Cabrera, J., Volant, P., Baker, C., Pettitt, W.S., Young, R.P., 1999. Structural and geophysical investigations in the EDZ (Excavation Disturbed Zone) in indurated argillaceous media: The tunnel and the galleries of the IPSN Tournemire site, France. In *Proceedings 37th US Rock Mechanics Symposium, Vail*. A.A. Balkema, vol. 2, pp. 957-964.

Carbonell, R, Perez-Estaun, A, Missana, T., Suso, J., Carretero, G., Bueno, J., Martinez, L, Buil, B., Garralon, A., Gomez, P., Hernan, P., 2006. Geology and geophysics of new boreholes at the FEBEX site. *2nd Annual Workshop Proceedings 6th EC FP-FUNMIG IP, Stockholm,* pp. 307-314.

Day-Lewis, F.D, Lane, J.W., Gorelick, S.M., 2004. Combined interpretation of radar, hydraulic, and tracer data from a fractured-rock aquifer near Mirror Lake, New Hampshire, USA. *Hydrogeology Journal* 14:1-14.

Döse, C., Gustafsson, J., 2011. Geological signatures of drillhole radar reflectors in Onkalo. Posiva Oy, Eurajoki, Finland, Working Report 2011-90.

Eberhardt, E., Diederichs, M., 2012. Review of Engineering Geology and Rock Engineering aspects of the construction of a KBS-3 repository at the Forsmark site – Initial Review Phase. SSM Technical Note 2012:39, Swedish Radiation Safety Authority (SSM).

Hakala, M., Siren, T., Kemppainen, K., Christiansson, R., Martin, D., 2012. In-situ stress measurements with the new LVDT cell – method description and verification. Posiva Oy, Eurajoki, Finland, Working Report 2012-43.

Heikkinen, E., Kantia, P., Lehtimäki, T., Silvast, M., Wiljanen, B., 2010. EDZ assessments in various geological environments using GPR method. Posiva Oy, Olkiluoto, Finland, Working Report 2010-04.

Joutsen, A., 2012. The use of geological data from pilot holes for predicting FPI (Full Perimeter Intersection) fractures. Posiva Oy, Eurajoki, Finland, Working Report 2012-12.

Karasaki, K., Apps, J., Doughty, C., Gwatney, H., Tiemi-Onishi, C., Trautz, R., Tsang, C-F., 2007. Feature detection, characterization and confirmation methodology. Final Report, NUMO-LBNL Collaborative Research Project, Lawrence Berkeley National Laboratory. U.S. Department of Energy Contract DE-AC02-05CH11231.

Khandelwal, M., 2012. Application of an expert system to predict thermal conductivity of rocks. *Neural Computing and Applications* 21: 1341-1347.

Kim Y-S., Sanderson, D.J., 2005. The relationship between displacement and length of faults; a review. *Earth-Science Reviews* 68(3-4): 317-334.

Kruschwitz, S., Taramanci, U., 2004. Detection and characterization of the disturbed rock zone in claystone with the complex resistivity method. *Journal of Applied Geophysics* 57: 63-79.

Kukkonen, I., Suppala, I., Korpisalo, A., Koskinen, T., 2007. Drill hole logging device TER076 for determination of rock thermal properties. Posiva Oy, Olkiluoto, Finland, Working Report 2007-01.

Lesparre, N., Gibert, D., Nicollin, F., Nussbaum, C., Adler, A., 2013. Monitoring the excavation damaged zone by three-dimensional reconstruction of electrical resistivity. *Geophysics Journal International* 195(2): 972-984.

Mustonen, S., Norokallio, J., Mellanen,S., Lehtimäki, T., Heikkinen, E., 2010. EDZ09 project and related EDZ studies in ONKALO 2008–2010. Posiva Oy, Eurajoki, Finland, Working Report 2010-27.

Ozkahraman, H.T., Selver, R., Isik, E.C., 2004. Determination of the thermal conductivity of rock from P-wave velocity. *International Journal of Rock Mechanics & Mining Sciences* 41: 703-708.

Paulamäki, S., Paananen, M., Kuivamäki, A., Wikström, L., 2011. Geological and geophysical investigations in the selection and characterization of the disposal site for high-level nuclear waste in Finland. *Geological Survey of Finland, Special Paper 4*: 131-144

Petersson, J., Stephens, M., Mattsson, H., Moller, C., 2012. Albitization and quartz dissolution in Paleoproterozoic metagranite, central Sweden - Implications for the disposal of spent nuclear fuel in a deep geological repository. *Lithos* 148: 10-26.

Sandberg, E.V., Olsson, O.L., Falk, L.R., 1991. Combined interpretation of fracture zones in crystalline rock using single-hole, crosshole tomography and directional borehole-radar data. *The Log Analyst* 32(2): 108-119.

Scullin, C.M., 1994. Subsurface exploration using bucket auger borings and down-hole geologic inspection. *Bulletin of the Association of Engineering Geologists* 31: 91-105.

SKB, 2010. Radionuclide transport report for the safety assessment SR-Site. SKB TR-10-50, Swedish Nuclear Fuel and Waste Management Co (SKB).

Silvast, M., Wiljanen, B., 2008. ONKALO EDZ-measurements using Ground Penetrating Radar (GPR) method. Posiva Oy, Eurajoki, Finland, Working Report 2008-58.

Sireni, S., 2011. Applicability of reflection seismic measurements in detailed characterization of crystalline bedrock. Posiva Oy, Eurajoki, Finland, Working Report 2011-24.

Sundberg, J., Back, P-E., Ericsson, L.O., Wrafter, J., 2009. Estimation of thermal conductivity and its spatial variability in igneous rocks from in situ density logging. *International Journal of Rock Mechanics & Mining Sciences* 46: 1023-1028.

Suzuki, K., Nakata, E., Minami, M., Hibino, E., Tani, T., Sakakibara, J., Yamada, N., 2004. Estimation of the zone of excavation disturbance around tunnels using resistivity and acoustic tomography. *Exploration Geophysics* 35: 62-69.

Coverage of SKB reports

Table 6: Coverage of SKB reports reviewed by the Consultants.

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, and Errata	S2, S4, 5, 10, 15	*Used as top level document.*
R-11-14, Framework for detailed characterisation for construction and operation	All	*Investigation programme to coincide with construction and operation.*
TR-10-52, Data report for the safety assessment SR-Site	6	*Geosphere data and related uncertainties.*
TR-10-21, Full perimeter intersection criteria	All	*Description of EFPC and its application.*
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-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-08-11, Effects of large earthquakes on a KBS-3 repository	All	*Description of analysis to determine respect distance and minimum size of discriminating fractures.*
TR-08-05, Site description of Forsmark at completion of the site investigation phase, SDM-Site Forsmark	5, 11, Appendix 4	*Site descriptions of deformation zones and fractures.*
R-08-116, Underground design. Forsmark Layout D2	All	*Reference for layout, construction sequence and qualitative risk analysis (addressing geological and geotechnical uncertainty). Spalling analysis reported in Appendix C.*

Reviewed report	Reviewed sections	Comments
R-08-83, Site engineering report Forsmark, Guidelines for underground design, D2	2	*Reference for influence of deformation zones on repository layout.*
IPR-08-10, Äspö Hard Rock Laboratory, Laser scanning combined with digital photography, Tunnel TASQ and niche NASQ0036A	All	*Description of use of laser scanning and photogrammetry for tunnel mapping.*
TR-07-01, Äspö Hard Rock Laboratory, Äspö Pillar Stability Experiment, Final report, Rock mass response to coupled mechanical thermal loading	All	*Description of visual observations, monitoring and mapping of spalling damage in large-diameter boreholes.*
R-07-45, Geology Forsmark, Site descriptive modelling Forsmark stage 2.2	2, 3, 5	*Description of geological and geophysical data collected and interpreted.*
TR-06-09, Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation Main Report of the SR-Can project	13.6	*Measures regarding spalling and controlling EDZ.*
R-06-39, Geological characteristics of deformation zones and a strategy for their detection in a repository	All	*Review of investigation methods for the detection of deformation zones and fractures.*
P-06-133, Forsmark site investigation: Boremap mapping of core drilled borehole KFM01C	Appendix 2	*Depth of borehole KFM01C to compare to RAMAC logging interval*
P-06-98, Forsmark site investigation: RAMAC and BIPS logging in boreholes KFM01C and KFM01D	3, 4, 5	*Description of RAMAC borehole radar system and logging coverage in previous use by SKB.*
TR-05-11, Äspö Hard Rock Laboratory Characterisation methods and instruments Experiences from the construction phase	7	*Details on geophysical borehole investigations.*
R-04-17, Respect distances: Rationale and means of computation	6	*Early reference to target fracture size.*
IPR-03-28, Äspö Hard Rock Laboratory: TBM assembly hall, Geological mapping of the assembly hall and deposition hole	2	*Mapping procedures for the deposition holes.*

2014:07

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.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se