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Technical Note

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Rock Mechanics related to long-term repository and site evolution

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SSM perspektiv

Bakgrund

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

Projektets syfte

Uppdraget är en del av granskningen som rör den långsiktiga utvecklingen av bergmassan omgivande det tilltänkta slutförvaret. Detta uppdrag fokuserar på att studera SKB:s hantering av kopplade THM-processer i berget samt den bergmekaniska utvecklingen över tiden med framtida perioder med stora klimatförändringar (permafrost, glaciation). Frågor som berörs är bland annat spjälkning, tillväxt av sprickor eller uppkomst av nya sprickor. Vidare berörs förändringar av bergspänningsfältet över tid, som också påverkar förändringar i transmissivitet. Förändringar i vattenflödet kan påverka de tekniska barriärernas integritet samt radionuklidtransport från eventuella skadade kapslar. En annan aspekt är möjliga seismiska händelser under den termala fasen.

Författarnas sammanfattning

Generellt sett visar SKB att de har en signifikant samling av hydrauliska, mekaniska och termiska data som är relevant för konstruktion av ett geologiskt slutförvar. Metoden för datainsamling är robust och följer gängse internationella metoder. Metodiken för säkerhetsanalys följer helt och hållet etablerad högkvalitativ teknologi och expertis, vilket resulterar i rapporter av hög kvalitet. Slutsatser dragna i rapporterna hänger samman med enskilda varierande geologiska- och mekaniska processer, som ofta är presenterade oberoende av varandra i ett flertal bakgrundsrapporter.

Med hänsyn till de många osäkerheter som förknippas med design och konstruktion av ett geologiskt slutförvar, vidden av geologisk data och säkerhetsanalys, bedöms kvaliteten på rapporterna vara hög. Granskade rapporter visar tydligt att SKB är väl bekanta med modern bergmekanik och bergteknik. Trots detta visar granskningen av de fyra rapporterna att det finns vissa begränsningar.

Resultaten från spänningsmätningar i Forsmark visar på stora osäkerheter. In-situ-spänningsmodellen som används i säkerhetsanalysen gjordes utan att ta hänsyn till de spänningsmätningar som är gjorda med hydrauliska metoder; därför behövs en bättre in-situ-spänningsmodell. SKB har i sitt modelleringsarbete inte tagit hänsyn till effekten av sprickutvidgning i samband med skjuvrörelser på grund av termisk spänning. Fortsatta analyser behövs för att kvantitativt uppskatta den förväntade sprickutvidgningen i samband med skjuvrörelser på grund av termisk påverkan samt relaterad förändring av permeabiliteten i det tilltänkta området.

Detta är viktigt eftersom denna förändring inte är reversibel och den ökade permeabiliteten inte kommer att vara fullt återhämtad även efter att slutförvaret svalnat. SKB har inte studerat förväntad lokalisering och magnitud av seismiska händelser under den termiska fasen. Bergmassans expansion på förvarsdjup på grund av uppvärmning förväntas generera seismiska händelser, spjälkning, skador under uttag av bergmassan och spänningsinducerade förändringar i sprickors permeabilitet. Dessa är alla undersökta av SKB utan att hänsyn tagits till att termisk spänning kan initiera nya sprickor eller att existerande sprickor kan förlängas. Fortsatta undersökningar för att beakta alternativa spänningsmodeller, termiskt inducerade skjuvrörelser och permeabilitet, seismicitet på grund av termisk last och tillvägagångssätt för sprickmekanik behövs.

Projektinformation
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Diarienummer ramavtal: SSM2011-3631
Diarienummer avrop: SSM2011-4398
Aktivitetsnummer: 3030007-4021

SSM perspective

Background

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

Objectives of the project

This assignment is part of the review regarding the long-term evolution of the rock surrounding the repository. This assignment focuses on the handling by SKB on the issues of coupled THM processes and the rock mechanical evolution over time with future changes in climate (permafrost, glaciation). Issues are for example spalling, propagation of fractures or initiation of new fractures. Considered are also issues regarding changes in stress field or transmissivity over time. Changes in the bedrock flow may influence the integrity of engineered barriers and radionuclide transport from potentially leaking canisters. Another issue is the potential for seismic events during the thermal phase.

Summary by the authors

In general, SKB demonstrates that they have accumulated a significant set of hydraulic, mechanical and thermal data that is essential for constructing a deep geological repository. The method of data acquisition is robust using the internationally- recognized and suggested methods. The methodology of safety assessment is firmly established by applying the state-of-the-art technology and expertise which results in high quality of produced reports.

Conclusions drawn in the reports are closely linked with various individual geological and mechanical processes, which are often independently presented in numerous background reports and published separately. Given the many uncertainties associated with designing and constructing a deep underground repository, the breadth of geological data and safety assessment, the quality of reporting is judged to be high. The content of the reviewed reports clearly demonstrate that SKB is well acquainted with modern rock mechanics and rock engineering. Nonetheless, there are a number of limitations noticed through the review of the four SKB reports.

Results from stress measurements conducted at Forsmark have a large uncertainty. The in situ stress model adopted in the safety assessment was constructed without making full use of the stress measurements with hydraulic methods; therefore a better in situ stress model is required. The effect of shear dilation due to thermal stress was not considered in the modelling work presented by SKB.

Further analyses are required to quantitatively estimate the expected shear dilation due to thermal loading and related change of overall permeability in the target area. Importantly, this dilation is not reversible and the increased permeability will not be fully recovered even after cooling of the repository. SKB has not studied seismicity and estimated location and magnitude of events during the thermal phase. The thermal expansion of the rock mass at repository level is anticipated to generate seismic events, rock spalling, excavation damage, and stress induced permeability change in fractures are all investigated by SKB without considering that thermal stress can initiate new fractures and existing fractures can propagate. Additional investigations are required to consider the alternative stress model, thermally-induced shear dilation and permeability, seismicity due to thermal loading, and fracture mechanics approach.

Project information

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Rock Mechanics related to long-term repository and site evolution

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Objectives of the project
This project is part of SSM:s review of SKB:s license application for final disposal of spent nuclear fuel. The assignment concerns review of rock mechanics related to long-term repository and site evolution at the Forsmark site covered in four SKB Reports.

Summary by the author
In general, SKB demonstrates that they have accumulated significant set of hydraulic, mechanical and thermal data that is essential for constructing a deep geological repository. The method of data acquisition is robust using the internationally- recognized and suggested methods. The methodology of safety assessment is firmly established by applying the state-of-the-art technology and expertise which results in high quality of produced reports. Conclusions drawn in the reports are closely linked with various individual geological and mechanical processes, which are often independently presented in numerous background reports and published separately. Given the many uncertainties associated with designing and constructing a deep underground repository, the breadth of geological data and safety assessment, the quality of reporting is judged to be high. The content of the reviewed reports clearly demonstrate that SKB is well acquainted with modern rock mechanics and rock engineering. Nonetheless, there are a number of limitations noticed through the review of the four SKB reports.
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1. Executive Summary

This review report is part of SSM (Swedish Radiation Safety Authority) Initial Review Phase of the SR-Site safety assessment with special focus on rock mechanics related to long-term repository and site evolution at the Forsmark site. The review covers the following four SKB (Swedish Nuclear Fuel and Waste Management Co.) reports.

- SKB (2011). SR-Site main report, SKB TR-11-01.
- SKB (2010). Geosphere process report, SKB TR-10-48.
- SKB (2010). Data report, SKB TR-10-52.
- Hökmark H, Lönnqvist M, Fälth B (2010). THM-issues in repository rock, SKB TR-10-23.

In general, SKB demonstrates that they have accumulated significant set of hydraulic, mechanical and thermal data that is essential for constructing a deep geological repository. The method of data acquisition is robust using the internationally- recognized and suggested methods. The methodology of safety assessment is firmly established by applying the state-of-the-art technology and expertise which results in high quality of produced reports. Conclusions drawn in the reports are closely linked with various individual geological and mechanical processes, which are often independently presented in numerous background reports and published separately.

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2. Introduction

This review report is part of SSM (Swedish Radiation Safety Authority) Initial Review Phase of the SR-Site safety assessment with special focus on rock mechanics related to long-term repository safety and site evolution at the Forsmark site. The review topics should also address the coupling between rock Mechanics and Thermal and Hydraulic processes (THM-modelling) for the planned spent fuel repository in the period following the final sealing of the facility. Cause and effect of rock deformation and failure, shear movements along pre-existing fractures, fracture initiation and propagation together with alteration of the flow and stress field at the site should be considered. The report intends to investigate the completeness of the safety assessment and technical soundness of the data and models established by SKB (Swedish Nuclear Fuel and Waste Management Co). The list of SKB reports that have been reviewed is shown in Appendix 1.
In view of the request by SSM, detailed analysis of specific issue is outside the scope of this review. Rather, suggestion of independent study was made in Appendix 3 where three topics are listed. Topic 1: Effect of thermo-shearing on the long-term performance of geological repository; Topic 2: Numerical analysis of seismicity induced by thermal stresses and Topic 3: THM coupling and fracture network evolution investigated by fracture mechanics approach.

This report is structured in the order of four mandatory SKB reports that were requested to review by SSM. In each report, review comments are divided into three categories: 1) general comments, 2) major technical comments, and 3) minor and editorial comments.

3. SR-Site main report (SKB TR-11-01)

3.1. General Observations

This document compiles the review comments on Swedish Nuclear Fuel and Waste Management Co (SKB)'s Technical report TR-11-01 Main report of the SR-Site, Volume I, II, and III. SKB presents purposes and general prerequisites of the safety assessment to investigate whether a safe spent nuclear fuel repository of KBS-3 type can be built at the Forsmark site in Sweden. Among others, this report contains a summary of Forsmark site investigation outlining the Rock Mechanical properties, deformation zones, rock stresses, bedrock hydraulic properties, integrated fracture domains, groundwater, bedrock transport properties and the surface system. Handling of external conditions and internal processes is an important component of the report followed by safety functions and their indicators. Analysis of a reference evolution is the main content in Volume II. In Volume III, selected scenarios and analyses of containment potential and retardation potential are presented with additional analyses and supporting arguments.

Major comments on SKB Report (TR-11-01) are listed in Table 1 and full explanation can be found in the following section 'Major technical comments'.

Table 1. List of major comments in the SR-Site main report (SKB TR-11-01).

	Major technical issues	Comments
1	SKB reported that the thermal conductivity has anisotropy ratio of 1.4.	There are reasons to expect that anisotropy is present also for strength and deformability. There is a need for a special study to determine the mechanical anisotropy, especially in terms of stress-induced effect and biased coring direction.
2	According to SKB report (TR-11-01), data suggested that a continuous EDZ would not develop in the Äspö rocks as illustrated in Figure 10-5 of the report.	The result was obtained during ideal conditions in the tunnel. The Posiva EDZ experiment conducted in one of the experimental niches in Olkiluoto show a continuous fracturing and hence EDZ in the wall and floor of the tunnel (Heikkinen et al., 2010). Comparative analysis is needed.
3	SKB has not presented estimations of the expected magnitude of earthquakes in the near-field and far-field during the thermal phase and of the likely ground motion of future nuclear power plants at Forsmark.	Further analysis on the impact of thermal loading on induced seismicity is necessary (Topic 2 in Appendix 3).

3.2. Major technical comments

SKB has made a major effort to determine the thermal conductivity and heat capacity of the major rock types at Forsmark and SKB has been successful in establishing relationship between density and thermal conductivity for the granite/granodiorite/tonalite group of rocks and for amphibolite. SKB needs to establish a better understanding of the spatial and size variability of the amphibolite xenolites in rock domain RFM045 of the target area. The present information from the few existing boreholes in the rock domain is not enough for design purposes and the lower tail of the thermal conductivity distribution together with the strong anisotropy of the amphibolite call for additional investigations.

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In Section 4.4.1 about formation and reactivation of deformation zones through geological times, SKB is suggesting the new idea that sedimentary loading is a process that besides tectonics gave rise to the build-up of high rock stress in the bedrock (p.116). Erosion and related unloading resulted in reactivation of existing gently dipping deformation zones and generation of dilatational joints and sheet joints of the type observed in the uppermost ca 100 m in the target area at Forsmark. Has SKB conducted any mathematical modelling to illustrate the suggested processes for reactivation of gentle dipping fracture zones and generation of sheet joints?

Almost all the boreholes in the target area are sub-vertical and slightly inclined and therefore there is a dominance of gently dipping foliation in the core samples that might influence the strength and deformability of the metagranite and granodiorite.

For the thermal properties of the main rock types in the target area, SKB has reported that the thermal conductivity parallel with the foliation, on average is a factor of 1.4 times greater than conductivity perpendicular to the foliation. There are reasons to expect that anisotropy is present also for strength and deformability and there is a need for a special study with the aim to determine the degree of anisotropy in strength and deformability of the dominant rock types in the Target Volume. Furthermore, fractured rock mass can be anisotropic due to the influence of anisotropic stresses. Min et al. (2005) conducted a numerical experiment on a fractured rock mass under various stress conditions and concluded that rock mass elastic modulus is highly stress dependent. Based on this result, it can be inferred that the fractured rock mass at Forsmark can be anisotropic with respect to maximum and minimum horizontal stress.

SKB claims that the orientation of the principal in-situ stresses and the magnitude of the vertical stress component (weight of the overburden) have the highest confidence in the stress model suggested for Forsmark. This statement is also in principle valid from the results obtained with the hydraulic methods although omitted by SKB. Instead SKB gives more confidence to the overcoring stress measurements in combination with indirect methods and by applying numerical analysis based on the current geological model. To reach the rock stress model, SKB is using old stress measurement results derived from the two boreholes DBT1 and DBT3 drilled in conjunction with the construction of the third power plant at Forsmark. These boreholes are located outside the target and candidate areas in other rock types. In addition the measurements conducted in these boreholes were done with the prototype of the of the Borre probe at great depth and without considering a modern type of quality assurance for each of the recorded data. It can be discussed if the presented results from the two boreholes at all are relevant for the stress model of the target area.

In Section 7.4.5 Geosphere, Table 7-6 Process Table, process Ge1 on heat transport, SKB claims that heat generation from the waste during excavation/operation can be neglected. Has SKB studied the case of a leaking canister in the deposition tunnel during emplacement? If the clean-up takes a long time due to leakage, the heat development in adjacent deposition hole can raise the temperature, which can prevent additional deposition and backfilling. More robust justification for not considering heat generation during excavation and operation phase is necessary.

For the same process Ge1, SKB claims that generation of earthquake due to heat transport is not relevant. Has SKB performed any mathematical modelling to demonstrate that thermal induced generation of earthquakes and its potential hazard to the nuclear reactors standing on ground in Forsmark is not relevant?

In Section 10.2.2 on the mechanical evolution of near-field rock due to excavation, SKB describes several Rock Mechanics concerns for the construction work such as development of an Excavation Damage Zone (EDZ), spalling and/or key block instability, reactivation of fractures and induced seismicity. All these issues are related to the state of stress, the strength of the rock mass and the orientation and geometry of the openings. The orientation and geometry of the openings can be selected once the state of stress at repository depth is known. The rock strength is known from the results of the laboratory testing and it is known to be high. The in-situ state of stress at Forsmark is by far the least known mechanical boundary condition for determining the rock mass response related to EDZ, spalling, reactivation of joints and fractures and the risk of induced seismicity. This raises the question of whether the presented in-situ state of stress in the Target Area at the repository horizon from one successful overcoring location in the deep borehole KFM01B together with indirect observations of stresses and data from adjacent borehole outside the Target Area can be acceptable for defining the stress state in a one-square-kilometer area at repository depth. Most Rock Mechanics experts would say no.

Furthermore, if SKB's estimation of the stress field at Forsmark is correct 100-200 deposition holes out of 6000 will suffer of spalling following excavation and all boreholes will develop spalling during the thermal phase. SKB has tried to demonstrate this in the CAPS (Counterforce Applied to Prevent Spalling) experiment in the TASQ tunnel of Äspö HRL (Lönnqvist et al., 2008). The results of the experiments were not conclusive. Hence, it still remains for SKB to demonstrate the development of EDZ in the deposition holes and the possibilities to mitigate extensive spalling during the thermal phase and, last but not least, to present best estimates of the hydraulic conductivity in the spalling zone.

In the same section of the report (10.2.2), SKB presents the view about formation of EDZ based on the results from the drilling and blasting excavation of the TASQ tunnel in Äspö HRL. SKB was using a technique to saw slabs from the walls of the tunnel and enhance the fractures by dying. Pictures from the surface of the slabs were analyzed by means of tomography to obtain a continuous picture of the developed EDZ from the blasting. Data suggested that a continuous EDZ would not develop in the Äspö rocks as illustrated in Figure 10-5 of the SKB report. One has to bear in mind that the result was obtained during ideal conditions in the tunnel. The Posiva EDZ experiment conducted in one of the experimental niches of the access tunnel of ONKALO in Olkiluoto where reflection and refraction seismic and ground penetration radar were applied show a continuous fracturing and hence EDZ in the wall and floor of the tunnel (Heikkinen et al., 2010).

Under the assumption that the stress state is of the magnitude as predicted by SKB or higher, spalling and reactivation of joints and fractures will develop and rock reinforcement with rock bolts, net and shotcrete will be needed. The extension of spalling and reactivation will be limited to the near-field of the tunnels and deposition holes. Since grouting can be applied in conjunction with excavation, the assumption of hydraulic conductivity being lower than $10^{-8}m^2/s$ in the vicinity of deposition holes and tunnels is likely to be achieved. In the thermal phase of the repository extension of pre-existing fractures and new fractures and spalling can appear and the limit of hydraulic conductivity and transmissivity is likely to exceed.

Induced seismicity due to excavation could impair the integrity of the already deposited canisters. According to SKB, this needs no further consideration in SR-Site. SKB has made a first estimate that an earthquake of magnitude 5 is needed in order for a fault slip larger than 0.05m to be triggered to harm a canister (p.781). SKB has to show what might be the magnitude of an earthquake around the repository area from thermally induced load at the time of maximum heat and thermal expansion of the repository. In addition SKB needs to determine the seismic risk and hazard to the existing nuclear facility on ground from the thermal phase of the repository.

In Section 10.3.5 SKB describes the mechanical evolution of the rock during the thermal period of the repository. On top of page 330, SKB presents a list of five mechanical processes that could have potential safety implications after closing the repository including reactivation of fractures in the near-field and far-field, crustal straining from the mid-Atlantic ridge push, rock fracturing and creep deformation. During the thermal phase of the repository, additional thermal stress reaches several tens of MPa in addition to the in-situ stresses and stresses from excavation may induce seismicity through the generation of new fractures or reactivation of pre-existing fractures and deformation zones. The seismicity from the repository might even develop at a time when the nuclear installations are still in operation or under decommissioning. SKB has not presented estimation of the expected magnitude of earthquakes in the near-field and far-field during the thermal phase and the likely ground motion on surface installations for the final repository and the present and future nuclear installations at Forsmark.

In the same Section 10.3.5, SKB presents the modelling approach with the distinct element code 3DEC. This code is thoroughly tested and applied in a large number of rock engineering applications worldwide . The code allows for mechanical and thermo-mechanical simulation of jointed and faulted rock masses. The calculated stress changes and related deformation of the discontinuities are used to assess potential changes in fracture or deformation zone transmissivity. Changes in fracture stress are related to changes in transmissivity and SKB has presented two different models of stress versus hydraulic aperture for Forsmark. Recent modelling with the rock fracture mechanics code FRACOD (Backers and Stephansson, 2011) show that fracture initiation, propagation and coalescence take place around the deposition hole during the thermal period and will develop to full extent during the glacial period due to the excess water head from the ice shield. It seems that SKB on the whole has left out a fracture mechanics approach to the problem of generation of new fractures or propagation of pre-existing fractures in the host rocks. Fracturing and related changes of groundwater flow is most relevant during the thermal phase and at the late stage of a glaciation cycle.

Section 10.3.5 and the geosphere process Ge6 is about the mechanical evolution of the rock during the thermal period of the repository. During the thermal phase of the repository additional thermal stress together with the virgin stresses and stresses from excavation may induce seismicity through the generation of new fractures or reactivation of pre-existing fractures and deformation zones. At present there is limited or no information about the rock mass response to large-scale heating with a temperature increase of 50-60 degrees at repository level. Since the rock mass at repository level in Forsmark has very few fractures there is limited yield ability and stress concentrations can build up at existing discontinuities or intersection of discontinuities which might lead to fracture initiation or fracture propagation. The thermally induced fracturing can generate seismicity. At present we do not know what magnitude the fracturing is able to generate in the hard and brittle rock mass at Forsmark. An on-going seismic activity during the excavation/operational phase is not wanted for safety reasons.

Many of the initial H-T-M-C phenomena in the repository system occur within the first 1000 year period. Furthermore, SSM's regulations require a more detailed description and safety analysis for this time period. The thermal evolution of the repository is of importance as input information to the mechanical, chemical and hydrogeological processes. One of the important design criteria requires that the buffer peak temperature does not exceed 100°C which means that the local rock heat transport properties are particularly important. For the SR-Site, SKB has studied this problem by means of a combination of analytical solutions, geostatistics, numerical modelling with finite element (FEM) and distinct element (DEM) methods, etc. In the future SKB needs to develop a special analysis package for designing the location of the deposition holes that contains the geology, thermal data, statistical distribution of the data, emplacement schemes with different geometry options and deposition sequences.

Chapter 14 of the report deals with additional analyses and supporting arguments. Section 14.4 is about verification that FEP's omitted in the earlier parts of the safety assessment are negligible in the light of the complete scenario and risk analysis. In Section 14.4.6, SKB lists the ten geosphere processes from Table 7-6 that are omitted from assessment for the whole or parts of the glacial cycle. The first issue deals with heat transport in the rock for the excavation/operational period of the repository. In conducting the thermal calculations SKB makes the assumption that all canisters are emplaced at the same time. In the same section SKB admits that this is not a likely order of canister emplacement and that there are situations where this does not apply. SKB needs to continue the studies about sequence of canister emplacement and present the rules for drilling the deposition holes and emplace the canisters.

As stated before about temperature development during the excavation and operational phase, SKB needs to develop a fully coupled, transient T-H-M-system that provides the options to analyze the thermal evolution for any possible geometry and location of the canisters in the deposition tunnels, individual panels and the whole repository considering the initial hydraulic and mechanical conditions.

In Section 15.6.1, SKB describes the further characterization of the deformation zones with potential to generate large earthquakes. There is certainly a need for additional work for developing the relationship of fracture length and fracture width and the characteristic deformation pattern, splays and deformability of the zones (Wells and Coppersmith, 1994).

In Chapter 15, Section 15.6.7 about Rock Mechanics conclusion, SKB admits that there are remaining uncertainties with respect to the magnitudes of the horizontal stresses with depth and the spalling strength. Both parameters are very important for all phases of the safety and constructability of the repository. SKB claims that the plans for Rock Mechanics assessment presented in the detailed investigation framework program (SKB R-11-14) are judged adequate. The section about Rock Mechanics, and stress measurements in particular, in the detailed investigation framework programme is about 1/3 of a page in length. SKB is encouraged to spend more time and resources on developing comprehensive analyses and research programs related to rock stress measurements and spalling at Forsmark.

In Section 15.5.12 about selecting deposition holes – mechanical stability, SKB describes the design criteria for placing the canisters in the vicinity of 3 km long deformation zones and the EFPC criterion. It was stated that it may be possible to reduce the respect distance of 100 m to some deformation zones based on a site-specific detailed and individual assessment. As such, the condition for reducing the respect distance is not clear and SKB needs to provide a specific condition to reduce the respect distance to large deformation zones.

3.3. Minor and editorial comments

The major part of the information in Chapter 4 is extracted from the final report SKB TR-08-05 containing the results of the site investigations at Forsmark. In a few places SKB has added new information or interpretation developed after publishing SKB TR-08-05. This new information is important for the correct evaluation of the SR-Site work, but difficult to find in the text. Occasionally new references are presented with the information that is not available in SKB TR-08-05. For example, twenty out of twenty four figures in this chapter 4 are from SKB TR-08-05, however, it is not certain whether the remaining four figures are providing new data that is different from the ones reported in SKB TR-08-05

In Section 4.4 about deformation zones, fracture domains and fractures, SKB has presented two-dimensional cartoons of the regional geodynamics showing the development and reactivation of different deformation zones in the Forsmark area (Fig. 4-11). The sketches illustrate the direction of bulk crustal shortening and related generation of mineral assemblages. There is a need of updating the cartoons and the geodynamic model considering new dating of minerals (p. 121) and geodynamics in the candidate area and surroundings.

SKB claims in Section 4.3.4 that there is generally a high confidence in the strength and deformability of the dominant rock types in the target area. The test results from the different mechanical parameters remained almost the same as new results were added from each of the modelling stages. This might be a direct result of the way of choosing samples for testing, which has been very selective in the site investigations. SKB needs to perform a special study of the most important mechanical parameters using another sampling method, more appropriate to a stochastic approach.

There are no rock mechanical data presented for the amphibolites appearing in the target volume. Also, amphibolite together with the major rock types should be tested for the degree of anisotropy.

Chapter 4 gives a description of the initial state of the site. In SKB:s terminology applied to the SR-Site project this corresponds to the natural, undisturbed state at the time of beginning the excavation of the repository. Based on the initial state, a repository design, including a site-specific layout, is developed in the project. Geosphere processes and alterations due to excavation, operation and closure are documented in the Geosphere Process Report and in the Underground Openings

Construction Report (SKB TR-10-18). The text gives the impression that there exists a report with this title. This is not the case for the construction. The report about construction in SR-Site is the following report: SKB (2009) Underground design Forsmark Layout D2 SKB R-08-116. The use of report name Underground openings construction instead of reference to the report SKB R-08-116 is confusing for the Reader of the SR-Site report. We are aware that the abbreviation referenced in the report is listed in Table 2-1, however, such information should be available at the beginning of the report.

In Section 4.6.1 about evolution of bedrock hydraulic properties, SKB analysis of transmissivity data versus normal stress suggest a poor correlation. Later in the text of Section 4.6.2 about hydraulic properties of deformation zones and fracture domains, SKB claims that there is a pronounced hydraulic anisotropy, where the largest transmissivity observed are associated with deformation zones that are oriented sub-parallel to the maximum horizontal stress. The text in section 4.6.2 seems to indicate that there is in fact a positive correlation between transmissivity data and stress orientation. SKB has to be more specific about which type of transmissive deformation zones is correlated with stress orientation and which are not.

In Chapter 8 about safety functions and safety function indicators, Section 8.3.4, Geosphere, SKB presents the conditions for providing mechanically stable environment by means of the design premises of: i) maximum 5 cm shear displacement ii) maximum shear velocity of 1 m/s for the canister and iii) favourable thermal conditions so that the rock temperature at repository depth should not fall below -4^{o}C. Freezing of the bentonite buffer might change the stiffness of the bentonite, which can lead to changes of other design premises including the limits for the maximum shear displacement and shear velocity.

In Section 10.3.4 about the thermal evolution of the near field, SKB presents some results from the numerical calculations performed and presented in the Site Engineering Report (SKB R-08-83). There is a need for conducting additional calculations about deposition sequences.

The geosphere process “Creep along fractures” (Ge8, Table 1-4, SKB TR-10-48) and in intact rock is neglected. For Forsmark fractures, SKB regards creep displacements to be insignificant compared to displacements caused by direct changes in load and pore pressure. Creep in intact rock will be restricted to small areas close to underground openings. SKB consider this to be taken care of in assessing thermally induced spalling. In justifying the negligence of creep in fractures and intact rock, SKB is referring to a study of Damjanac and Fairhurst (2010). The Authors of the study have made a compilation of different theoretical and experimental studies with the aim to provide evidences for a long-term strength threshold in crystalline rock. The major part of the study is about stress corrosion and numerical and theoretical analysis of crack propagation by stress corrosion. The authors have used the classical geometry of an inclined fracture in an elastic plate subjected to axial and lateral loading. In analyzing the wing-crack generation and propagation for both the analytical and numerical model they have omitted the influence of stress intensity from shear loading and fracture toughness in shear. The agreement between the theoretical and numerical modelling results is good but the discrepancy between the applied fracture toughness and the true value is too large (2.4 MPa·$m^{1/2}$ versus 3.1 MPa·$m^{1/2}$, p. 523 of the paper). This error can be due to the left out of the shear component in the modelling. The increase of confinement will enhance the importance of shearing but in the theoretical and numerical analyses this is only done by suppressing the tensile Mode I fracturing. Therefore, this study and its application to stress corrosion and creep should have also considered the shear Mode II fracturing in the modelling.

4. Geosphere Process Report (SKB TR-10-48)

4.1. General observations

This report gives information about the processes in the geosphere of importance for the long-term safety of the repository for spent nuclear fuel in Sweden. The technical report is one of the key-reports in SKB's safety report SR-Site.

The aim of the SKB TR-10-48 Report in relation to the SR-Site is to identify and illustrate relevant long-term safety issues and their evolution over time. The content of the report forms one of the eleven brick-stones (No 4, "Compilation of Process reports with handling prescriptions including models") of the SR-Site safety assessment scheme (Fig. 2-2 and Ch. 7 in Volume I of the Main Report of the SR-Site project). Each geosphere process is presented according to seven different headings similar as was applied in the safety report SR-Can (SKB TR-06-19).

The main scenario for the processes described in SR-Site encounters the following ca 120,000 years of evolution corresponding to a Late Pleistocene glacial cycle. Knowledge about the glacial cycle is based on the evolution of the last glacial cycle (Weichselian) on the northern hemisphere. This is described in more detail in the SR-Site Climate Report. The following time periods are used in the Process Report to reflect different conditions of relevance for the repository performance:

- excavation/operation period
- initial temperate period
- periods of periglacial climate domain
- periods of glacial climate domain

In addition to these periods, the handling of different processes in case of earthquakes is specifically addressed. SKB considers earthquakes as external events that can affect the mechanical properties of the repository and its surrounding which can have impact on the engineered barriers.

The initial state of the site at Forsmark is defined by SKB as that of the natural system as given by the site investigations prior to excavation of the underground openings and construction of the repository.

In Section 1.6 of the Process Report, SKB presents in Table 1-4 how processes in the geosphere will be handled in different time frames and climate domains and in addition for the special case of earthquakes. SKB presents in Table 1-4 processes in the geosphere describing how processes will be handled in different time frames and climate domains and in addition for the special case of earthquakes. The importance of the processes for the long-term safety is illustrated with three different colours describing neglected processes (green), processes that are quantified by modelling in the safety assessment (red) and processes that are neglected subject to a specified condition (orange).

Following processes are presented by SKB and commented upon in this review:

1. Heat transport
2. Freezing

3. Groundwater flow
4. Displacement in intact rock
5. Reactivation – displacement along existing discontinuities
6. Fracturing
7. Creep

A selection of m ajor comments on SKB Report (TR-10-48) are listed in Table 2 and full explanation can be found in the following section 'Major technical comments'.

Table 2. List of major comments from Geosphere Process Report (SKB TR-10-48).

	Major technical issues	Comments
1	Experimental results show that there is anisotropy in thermal conductivity in Forsmark rock.	Thermal modelling considering the anisotropy needs to be conducted.
2	Temperature dependency of heat capacity and thermal conductivity were not measured.	Temperature dependency of heat capacity and thermal conductivity needs to be measured and its effect on the design of repository and long-term safety needs to be investigated.
3	SKB claims that the widening and freezing of fractures during periglacial and glacial periods may be reversible.	There is no sufficient supporting data on this and further investigation needed for irreversibility.
4	A slot between bentonite buffer and rock can induce drying of the bentonite and temperature may exceed the threshold of 100 degrees.	Modelling is needed to give confidence about the function of buffer in case of drying bentonite and increased gap between bentonite and rock.
5	SKB claims that heat transport is not an issue for the induction of earthquakes.	Thermal energy from over 6000 canisters may be enough to induce earthquake and harm the surface nuclear power plant at Forsmark. Further analysis needed (Topic 2 in Appendix 3).
6	Process of "over-closure" of rock fractures is missing.	The process of changing aperture during repeated loading and unloading needs to be studied (Topic 1 in Appendix 3).
7	The likelihood of subcritical crack growth was not sufficiently investigated.	This needs to be explored (Topic 3 in Appendix 3).

4.2. Major technical comments

Modelling of heat transport in natural material is a straight forward process and numerous modelling and experimental studies have confirmed the overall satisfactory in simulation heat transport in homogeneous, isotropic geological material. SKB has also conducted long-term experiments within the Äspö Prototype Repository experiment in the Äspö Hard Rock Laboratory together with 3-D thermal modelling which show good agreement between experimental and modelling results (SKB IPR-07-01).

Experimental results of heat conduction and thermal expansion of Forsmark rock have shown that rocks at Forsmark have anisotropic thermal properties. However, SKB need to arrange a series of test with the so-called TPS (Transient Plane Source) method or similar to present data about the degree of anisotropy for the main rock types in the repository. In addition SKB has to present how thermal modelling work will be conducted considering the anisotropic behaviour in designing the tunnels and deposition holes and how the results will influence the long-term safety of the repository.

The rock mass at Forsmark contains inclusions and xenolites of aplite, amphibolite and other secondary rock types. SKB has not demonstrated how the design of the deposition holes will be made for situations when these structures appear at the original location of the deposition holes and nearby. Also, SKB has not presented any methodology and technique to determine the geometry, size and fabric of the xenolites at the repository depth of the target area.

In section 2.1.2 about dependence between processes and geosphere variables it is correctly stated that thermal conductivity and heat capacity are temperature dependent. So far SKB has not presented conductivity and capacity data as a function of different temperature nor of mechanical confinement. Later, if experimental results show that thermal conductivity and capacity are temperature and pressure dependent, SKB has to demonstrate the ability to consider this in the thermal modelling for design of the repository and long-term safety.

The presence of fractures in the rock mass and in particular open fractures and new generated fractures will somewhat reduce the thermal conductivity. The compressive stress magnitude at repository level will tend to close or shear the fractures and therefore, the change in rock mass thermal conductivity and capacity is probably of minor importance for the heat conduction.

During periglacial and glacial periods water in fracture will freeze (9% volume increase) and the expanding ice will generate a swelling pressure in the fractures. SKB claims (p.35): “there can be widening of fractures due to freezing but the effect is probably reversible as thawing takes place.” SKB has to find evidences for this statement and also include the swelling pressure in the modelling of the rock mass response in the near-field. Alternatively, following thawing remaining displacement (normal and/or shear) can cause an increased fracture aperture and thereby enhance flow in the near-field. The increased aperture of the fracture can be due to loose material of the fracture walls acting as a propants to keep the fracture open.

Section 2.1.3 in the SKB report is about the boundary condition of thermal processes and this section describes the heat conduction at the buffer/bentonite boundary. If there is a slot between the bentonite buffer and the rock, the bentonite might dry and the system is no longer working as expected. If the slot is filled with bentonite pellets, the thermal conductivity becomes lower. This may enable the temperature to exceed the threshold of 100 degrees and thereby start the alteration of the buffer. SKB ought to present modelling results and laboratory experiments to give confidence about the function of the buffer in case of drying the bentonite, increased gap between the buffer and rock wall and contracting and fracturing of the bentonite.

Section 2.1.5 is about natural analogues/observations of thermal processes in nature. SKB has stated that this headline is not applicable to thermal processes and heat. However, we know from the field of oil, gas and geothermal extraction of heat, that modifying the temperature in a reservoir or large rock mass might lead to earthquake activity and related fracturing of the rock mass. This is an area of research where SKB has to be better informed.

In Section 2.1.7 Handling in the safety assessment SR-Site, SKB claims that "heat transport is not an issue for the induction of earthquakes" (p. 31). This statement needs to be looked into. The question is if the loading of the large rock volume of the repository and its surrounding with the thermal energy from the more than 6000 canister of spent nuclear fuel provides enough energy to initiate and propagate fractures in the sparsely fractured rock mass at repository depth in Forsmark. In addition it is necessary to study whether there is a risk of tremor or earthquakes from the repository that can affect or disturb the energy production from the nuclear reactors at Forsmark.

The fundamental safety functions of the bedrock are to give mechanical stability to the engineered barrier system and to retard radionuclide transport to the biosphere. The introduction to the chapter about mechanical processes contains an overview of the mechanical evolution of the Baltic Shield and the most recent results about strain measurements, postglacial faulting and the mechanical properties of the repository rock mass (strength, deformability and stress).
In the safety assessment of the mechanical properties in Section 4.1.5, SKB has made the following subdivision of the processes:

- Displacement in intact rock
- Reactivation of discontinuities
- Fracturing
- Creep displacement.

To illustrate the different processes, SKB presents a schematic picture of a rock mass with discontinuities and a circular opening subjected to a non-uniform stress field (Figure 4-1). The information related to each of the main processes listed above gives a clear overview of the individual processes and their dependencies on the defined geosphere variables for each of the phases of the repository (Fig. 4-1 and Table 4-1). The presentation of each of the processes shows that SKB is well acquainted with the fundamentals of Rock Mechanics and its application to Rock Engineering.

Section 4.3 is about reactivation and displacement along existing discontinuities. The general description of the processes involved and the relative importance of normal versus shear displacement and their combination to generate mixed mode displacement in rock engineering applications are correct and relevant. SKB also admits that the shear component is anticipated to be much larger than the normal component at repository depth. This statement is important for the likelihood of permeability changes due to slip and shear displacements of deformation zones and large fracture and related permeability change. The coupled hydro-mechanical properties of deformation zones and large fracture and the representation as single fractures in the modelling need additional analysis.

There is one process about normal displacement of single joints and fractures that has not been mentioned by SKB in the Geosphere Process Report. It is called "over-closure" and is a type of hysteresis observable in the recording of normal displacement versus applied stress. Over-closure comes from the fact that when a fracture is loaded in normal direction, displacement is observed. If the fracture is later unloaded, a permanent displacement remains. Hence the fracture is not fully elastic. During the different time phases of the repository the fractures in the vicinity of the deposition hole undergo several cycles of loading with different magnitudes and orientations (swelling, heating, cooling, glaciation, deglaciation and tectonics). These repeated loadings and unloading can generate permanent deformations that lead to aperture changes of the fracture and modified transmissivity of individual fractures or fracture system. The process of over-closure of joints, fractures and rock mass for the repository at Forsmark need to be analysed by SKB.

The APSE pillar experiment conducted in Äspö HRL has been of great importance for the understanding of the fundamental processes of rock spalling in the wall of the deposition holes. The experiment gives important data about the onset of microcracking and crack initiation strength of the rock and the geometry and development of the breakout with respect to thermal loading and filling support. The CAPS experiment following the APSE pillar experiment aimed at studying the influence of small support pressure to mitigate spalling. This experiment was not conclusive as there was large difference in the amount of spalling observed in the different boreholes. The non-conclusive results of the CAPS experiments, the possibility of creep failure and the lack of permeability data in the spalling zone call for additional experiments and related modelling of the coupled T-H-M processes and related rock fracturing and subcritical crack growth.

In Section 4.4.7 about handling of rock fracturing in the safety assessment, SKB describes the likely processes for each of the four different phases of the repository with time and the influence of earthquakes. SKB states that “fracturing directly associated with earthquake faulting is included in the rupture propagation model used in the earthquake simulations without detailing the nature of the process” (p. 115). It is not clear what rupture models SKB refers to and there are no references presented except references to case studies of earthquake-induced damage of underground facilities. SKB has not considered the possibility of earthquake generation and related shearing of pre-existing fracture and rock fracturing due to the heat load generated by the spent nuclear fuel during the thermal phase.

Section 4.5 describes the process of creep, meaning the time-dependent deformation. For large deviatoric stresses, rock material deforms with time (primary and secondary creep) followed by accelerating creep and finally failure. For low stresses and corrosive chemical environment, rock crystals and in particular quartz are weakened and the surface energy of the microcracks is reduced. This reduces the fracture toughness of the rock and allows fractures to grow at low speed under a process called “subcritical crack growth”. Creep of intact rock in the near-field parts of the repository is only likely in the high-stressed areas in the vicinity of the deposition hole and with preference where stress concentration appears such as the area of spalling in the walls of the deposition hole or at the top of the hole close to the tunnel floor. Creep is enhanced with increasing temperature and the time span with excess heat in the repository. Subcritical crack growth is likely to develop in rock bridges between pre-existing fractures or any other imperfections in the rock mass where stress concentrations develop. This phenomenon has not been considered in SKB’s site investigation or research and development program but needs to be explored. The work by Damjanac and Fairhurst (2010) for SKB about fracture growth by stress corrosion is not particularly relevant as it only considers Mode I (tensile fracture propagation) at the tip of the growing fracture.

In Section 4.5.7 about handling of creep processes in the safety assessment SR-Site, SKB discusses the possibility of generating large creep displacements along discontinuities by a mechanism where the stress of the discontinuity decreases to zero. As pointed out by SKB and supported in this review this is not a likely process since we always observe deviatoric rock stresses in the underground. What is not considered in the analysis by SKB is the possibility of fracture propagation and coalescence of fractures. SKB illustrates the process in Figure 4-1 of the report but does not make an attempt to simulate the creep process with a fracture mechanics approach. There are always fractures in the rock mass with a favourable orientation to generate high stress concentrations at the tip of the fracture with respect to the existing far-field stress. These are areas where subcritical crack growth and creep are most likely to develop and where fracture will coalescence and groundwater flow can short-circuit.

4.3. Minor and editorial comments

A new stochastic method for determination of thermal conductivity based on mineral composition of the rock mass has been developed by SKB during the time of the site investigations. The method is new and innovative and its application to SKB's site investigations has been reviewed and found adequate by the INSITE group of SSM. SKB is also aware of the importance of the tails of the distribution of thermal conductivity for a proper design of the tunnel and canister central distance not to exceed the critical limit of 100°C in the buffer.

For stress-deformation analyses of both the displacements in intact rock and reactivation of discontinuities, SKB has used the distinct element method and computer codes UDEC (2-D) and 3DEC (3-D). There is no doubt that the codes are properly validated against analytical solutions and that the SKB consultants are well acquainted with the codes and their capacity. The results presented and their importance for the short and long term safety would be stronger if SKB had been using several different modelling approaches and different computer programs and several consultants.

The 3DEC analysis performed for intact rock and rock mass response is of utmost importance for the confidence building of the application of 3DEC for analysis of the rock mass response to swelling pressure of the buffer and the thermal loading from the spent fuel. These modelling studies and experimental studies performed by SKB at Äspö HRL could have been given much more space and explanation in Section 4.2.4 of the report.

SKB and its consultants have been using the analytical solution be Eshelby (1957) to calculate the maximum deformation in the centre of a fracture in an elastic medium. The displacement is dependent upon the stress field, orientation and length of the discontinuity and the mechanical properties (friction angle) and elastic properties of the rock mass. It is time for SKB to look into more modern approaches to analyse slip displacements as a function of fracture size and rock properties.

In section 4.1.1 about overview and general description of fracturing processes, SKB starts the section by writing about the fundamental mechanisms and Griffith's original fracture theory from 1924. Thereafter the Authors make the giant step forward till today and claim that the most widely used failure criterion for describing the strength of intact rock and rock masses is the empirical failure criterion by Hoek/Brown. There is a need for a more complete description of the fracture mechanics approach to rock strength and there are many more criteria applicable to intact rock and rock masses. A better way of describing rock fracture criteria is to use the two groups of criteria: mechanistic and phenomenological failure criteria. Fracture mechanics belongs to the mechanistic group while Hoek/Brown failure criterion is of phenomenological type. The credibility of SKB’s presentation would be enhanced by combining the two groups of criteria in their approach.

5. Data Report (SKB TR-10-52)

5.1. General observation

The aim of the report in relation to the SR-Site is to illustrate and qualify data relevant for the long-term safety of the repository and its evolution over time. The contents of the report forms one of the eleven brick-stones (No 6, “Compilation of input data”) of the SR-Site safety assessment scheme. In compiling the data for the safety assessment, SKB has been using information from supporting reports and documents including data reported in SR-Can reports. In addition SKB has produced new data sets for the particular purpose of assessment of SR-Site safety. The compilation of data in the Data Report is presented in five chapters: spent fuel, copper canister, buffer and backfill, geosphere and surface system. The majority of data are compiled from supporting reports and documents. By far the largest number of data is derived from the site investigations at Forsmark and the related site description documents.

The identification of essential input data to the safety assessment comes from Assessment Model Flowcharts (AMFs). The flowcharts are produced from information derived at other steps of the safety assessment in the project or from experience gained in other safety assessments like SR-97 and SR-Can.

Major comments on SKB Report (TR-10-52) are listed in Table 3 and full explanation can be found in the following section ‘Major technical comments’.

Table 3. List of major comments from Data Report (SKB TR-10-52).

	Major technical issues	Comments
1	SKB has decided to present two different approaches (AMF and a parallel approach) for selecting data and performing the safety analysis.	Clearer explanation as to why these two approaches were necessary needs to be given.
2	Moderate anisotropy in thermal conductivity is measured.	Corresponding modelling that considers the anisotropy of thermal conductivity needs to be conducted in order to be used for repository design.
3	Thermal conductivity and heat capacity are temperature dependent.	SKB has to investigate the impact of temperature dependency on design of the repository and long-term safety.

5.2. Major technical comments

It is not clear from reading Section 1.2.2 of the report why SKB has decided to present two different approaches (AMF and a parallel approach) for selecting data and performing the safety analysis. Radionuclide transport is a part of AMF like many of the other processes, but why this part was treated separately and analysed with two different approaches remains a question. For the radionuclide transport modelling a slightly different approach has been used in that data for application of the two computer codes COMP23 and FARF31, have been collected, evaluated and applied. The quotation of the regulators' view and SKB's answer does not help in understanding the reason behind applying the two different methods. Is it so that radionuclide transport is more important than, for example, groundwater flow and composition, THM saturation, corrosion, buffer erosion etc. and therefore needs special data requests? SKB needs to clarify these issues.

In Section 1.3 SKB describes the participating parties in developing the Data Report. To make it clear how the different parties in the process of data handling have contributed, SKB has adopted the terminology of data supplier, customer and the SR-Site team. This terminology is in line with that used in existing QA system between the parties within SKB organisation. The improvement of the data selection, data transfer and quality assurance in the safety assessment SR-Site is certainly better compared to SR-Can.

Section 2.1 of the Data Report is about identifying data via Assessment Model Flowcharts. For the SR-Site SKB presents two different flow charts, the first describing the excavation/operation and initial temperate period (Fig. 2-1) and the second describing the permafrost and glacial conditions (Fig. 2-2). Each blue box in the flowcharts represents a subject area in the Data Report and is labelled according to the individual main sections in the report. The modelling activities and assessment of the results are also presented in the figures. In the way the flowcharts are designed, they are representing the logics and sequence in which the modelling is performed. When comparing the information in the flowcharts with the section numbers, data provided and primary supporting reports presented in Tables 2-1 through 2-5, there are missing links. Comparing the information in Table 2-4 with the two flow charts the follow questions are raised:

- Why is Rock Mechanics (DR 6.4) omitted in AMF 2 flowchart? Both DR6.4 rock mechanics and DR6.5 Spalling and excavation damaged zone are linked with AMF1 and AMF2 according to Table 2-4.
- Why is the white box Layout D2 presented in flowchart AMF 2 but omitted in AMF 1?
- Where is excess pressure from bentonite freezing considered in AMF 2?

The flowcharts and the tables about couplings need to be checked for consistency and completeness and additional modelling work of importance for long-term safety not presented in the flowcharts or tables should be listed.

Experimental results of heat conduction and thermal expansion of Forsmark rocks have shown anisotropic thermal properties. SKB needs to arrange a series of test with the so-called TPS method or similar to present data about the degree of anisotropy for the main rock types in the repository. In addition SKB has to present how thermal modelling work will be conducted considering the anisotropic behaviour in the design of the tunnels and deposition holes and how the results will influence the long-term safety of the repository.

5.3. Minor and editorial comments

Qualification of input data and instruction to the supplier and customer are presented in Section 2.3 of the Data report. The stages of writing and reviewing the data comprised in the Data Report follows a standard outline presented in five stages from A to E. The supplier of data to the SR-Site team is asked to follow eight sections with clear instructions about documentation, uncertainties, variability and correlations. The presented system is rigorous and ambitious and provides confidence in the way data is collected and presented.

6. THM-issues in repository rock (SKB TR-10-23)

6.1. General observations

This report addresses the thermo-hydro-mechanical (THM) evolution of the repository host rocks that SKB finds of importance for the safety assessment of a KBS-3V type spent nuclear fuel repository at the Forsmark and Laxemar sites. The Laxemar analyses are not given with the same level of detail as those for Forsmark. SKB presents modelling results from three scales of models: Small scale (40×40×40 m), Medium scale (200 m × 200 m × 200 m) and Large scale (8×7.5×3 km) based on data from Forsmark and Laxemar. A three-dimensional discrete element modelling using 3DEC (Itasca, 2007) related to Laxemar is presented in Appendix I of the report.

During the preparation work for presentation of SR-Can and now SR-Site, SKB has performed an impressive series of modelling work related to the performance and safety aspects of THM processes and evolution for the most critical phases of the repository evolution with time. The modelling has been performed at a different scale and by using a number of different input parameters, boundary conditions and geometries in order to take into account the associated uncertainties. The extensive consideration of these parameters reduces the conceptual uncertainties in assessing the safety. Nonetheless, a few major questions are raised in terms of the variability of fracture properties under a given stress condition as will be explained later in the major comments.

The report covers the evolution of rock temperatures, rock stresses, fracture transmissivity during excavation and operational phase, temperate phase and a glacial cycle at various scales. The focus of the study was on the spalling in the walls of the deposition hole and the changes in the transmissivity of fractures and deformation zones. All analyses were conducted by a three dimensional distinct element program, 3DEC, and, to a lesser extent, by analytical solutions. The report also contains results of extensive parametric studies. In general, the quality of the figures and graphs, and the corresponding explanations are clear given the complexity of the coupled phenomena. On the other hand, each of the topics covered in this study, e.g. stress-driven transmissivity change, deserves more in-depth independent study. This report somewhat overlooked several aspects, as listed in Table 4 of this review report, that really should have been investigated more thoroughly.

In terms of methodology, a three dimensional distinct element program 3DEC was the main tool. Even if 3DEC is capable of considering elasto-plastic behaviour of a fracture, the application in this report is limited to the linear elastic case. Furthermore, explicit consideration of rock fracture was considered only at a medium scale (200 m × 200 m × 200 m).

The hydro-mechanical process considered in this study was conducted without explicitly including hydraulic processes in the modelling. Rather, fracture apertures were converted into transmissivity as a main parameter for hydro-mechanical investigation. This approach is useful. However, it is far from comprehensive. Fluid flow pathways are governed by the connectivity of the fractures and the channelled fluid flow is a prevalent mechanism that is observed in nature. Only a few fractures that have large transmissivity can change the fluid regime, therefore explicit modelling of fluid flow through the rock mass is necessary (Min et al., 2004; Min and Stephansson 2009).

Details of review comments will follow as we discuss issues chapter by chapter. Already from the beginning of performing research and development related to deep geological disposal of radioactive waste in Sweden and elsewhere, more than 35 years ago, the theoretical and numerical modelling of rock mass response to heat have shown a close agreement with experimental results in the laboratory and from field experiments. This has given a great confidence about the ability and capacity to predict the rock and rock mass response to thermal loading in time and space. In this field, SKB has played an important role in reaching this confidence by performing thermal tests of various scale and complexity at the Stripa Mine and at Äspö HRL. SKB has supported the theoretical and numerical development of thermal calculations for radioactive waste disposal by e.g., Claesson and Probert (1996). Unfortunately, SKB is not making full use of this knowledge and experience in the arguments for predicting rock mass THM response to heating and the safety aspects of the rock mass response. So for example, the existing results from the on-going long-term heater tests for the Prototype Repository Test for the KBS-3 concept at Äspö HRL (SKB IPR-07-01) are not brought in to this study of the THM-issues for SR-Site and a potential repository at Forsmark. For example, the fact that the convection through the deposition tunnel can be neglected based on the Prototype Repository study could be mentioned.

Similar to the SR-Can assessment of the potential impact of the different THM processes, the evaluation in SR-Site is made by using a combination of numerical models and analytical solutions. This approach has given good agreement between analytical and numerical results which gives confidence in the final results. The main modelling tool is the three-dimensional distinct element code 3DEC which is specifically developed for simulating mechanical response of discontinuous rock masses to loading and heating. The code can treat individual or sets of discontinuities in the rock mass. The discontinuities have to be through-going in the model. Short fractures can be simulated by giving the outer parts of the fractures high strength and low deformability. However, the major weak point of the code is the inability to simulate fracture initiation and propagation. This issue will be further discussed in a separate paragraph under Section 6.2 Major technical comments. The current version of 3DEC has thermal logics included to simulate time-dependent heat sources like the canisters with their heat output individually or in regular arrays.

The THM impacts of an developed excavation damage zone (EDZ) around the excavations in the repository are not included in the report and this makes it difficult to judge the combined effect of excavation damage and stress induced deformations and failure, and their influence on the performance and safety of the potential repository at the two sites.

Major comments on SKB Report (TR-10-23) are listed in Table 4 and full explanation can be found in the following section ‘Major technical comments’.

Table 4. List of major comments from SKB TR-10-23.

	Major technical issues	Comments
1	Transmissivity change induced by shear dilation of fractures was ignored and not quantified.	Shear dilation can be significant even under moderate normal stress (5-25 MPa).(Topic 1 in Appendix 3)

2	Fracture network propagation and initiation was not properly considered	Both tensile and shear failure mode criteria need to be applied for fracture propagation and initiation. (Topic 1 in Appendix 3)
3	Only mechanical aperture change, which was converted into transmissivity, was investigated as possible fluid flow change without explicit modelling of hydraulic process.	Fluid flow is much affected by connectivity and this cannot be replaced by mechanical observation. Explicit hydraulic calculation in discrete fracture network is necessary. (Topic 1 in Appendix 3)
4	The stress field calculation was largely based on continuum modelling even if the tool 3DEC is capable of considering fractures.	Effect of the existence of fracture on thermal stress needs to be investigated (Topic 3 in Appendix 3)
5	Microseismicity induced by thermal stress is underestimated.	Quantitative evaluation is required (Topic 2 in Appendix 3).
6	Fully coupled THM modelling was not applied for the glaciation and permafrost stage	Coupled calculation using existing code can be possible, e.g., ABAQUS, FRACOD (Topic 3 in Appendix 3).

6.2. Major technical comments

In the review of SKB TR-10-23 the comments are presented chronologically for each of the main chapters of the report.

Chapter 2 of this report is about the scope of the study and in particular the modeling approaches for the different periods of the repository development like excavation, operational period, initial temperate period, permafrost and glaciation periods. In Section 2.3.1, SKB claims that during the excavation activities (construction and operational phases) there will be stress redistributions around the openings and that these redistribution effects will not reach more than a couple of diameters of the opening away from the opening peripheries. Therefore, there will be only local effects on the groundwater situation caused by shear and normal displacement of the fractures around the openings. This results from the elastic modelling with the 3DEC code. If fractures in the 3DEC models were allowed to propagate from the tip of existing joints and coalescence with other existing and newly generated fractures, the influence can reach a larger distance away from the deposition holes and tunnels. The effects of propagation and coalescence become most important during the initial temperate period, when the temperature in the near-field region around the canister hole reaches the maximum and also during the glaciation period. The most recent modelling with the rock fracture mechanics code FRACOD (Backers and Stephansson, 2011) shows that fracture initiation, propagation and coalescence takes place around the deposition hole during the temperate period due to swelling pressure of the buffer and will develop to full extent during the glacial period due to the excess water head from the ice sheet. FRACOD was developed by Shen and Stephansson (1993) and simulates complex fracture propagation in rocks governed by both tensile and shear mode fracture mechanisms.

When SKB presented the results for SR-Can, fracture mechanics was applied to determine the probability of fracturing of pre-existing fractures from an earthquake located in the vicinity of the repository. It seems that SKB on the whole has left out the fracture mechanics approach to the problem of generation of new fractures or propagation of pre-existing fractures in the host rocks.

In Chapter 3, Section 3.2, SKB is presenting the arguments for not considering the generation of new fractures or propagating of pre-existing fractures. SKB claims that high maximum/minimum stress ratio is needed for generating new fractures and that confinement suppresses time-dependent fracture growth since fracture growth requires tension at the tips of the propagating fracture. The recent rock fracture mechanics study conducted by Backers and Stephansson (2011) shows that fracturing and fracture propagation develops in the rock mass surrounding the canister holes for the stress magnitudes and confinement during the temperate and glaciated phase of the potential repository at Forsmark. Fracture initiation and propagation cannot be simulated with the distinct element code 3DEC that SKB has applied in their study.

Chapter 3 deals with approaches to evaluate modelling results. In Section 3.1, SKB describes how the load scenarios will be evaluated with regard to spalling in the periphery of the openings and the transmissivity changes of the existing water-bearing fractures. Also, SKB explains that formation of excavation disturbed/damaged zone (EDZ) and propagation and coalescence of existing water-bearing fractures are not addressed in the report. SKB’s reason for not considering propagation and coalescence of existing fractures is motivated in Section 3.2. SKB admits that fracture frequency, size and orientation of individual fractures and connectivity between fractures may potentially change because of fracture propagation and coalescence when the rock stresses change as a result of mechanical and thermo-mechanical loads. Fracture initiation, propagation and coalescence are most likely to occur close to the openings and are favored by high stress levels and high stress ratios between the magnitude of the maximum and minimum principal stress. SKB quotes a SKI report from 1996 where Shen and Stephansson (1996) conducted modelling with the Displacement Discontinuity Method and an early version of the code FRACOD. With the selected input parameters, model geometry and boundary stresses they found at that time how rather high stress ratios were needed to initiate and propagate pre-existing fractures. One has to keep in mind that at the time Shen and Stephansson (1996) was published, material parameters for fracture toughness of rock and in particular shear toughness data were not available. From the mid 90’s, the code has been extensively developed and the latest version 4.0 has recently been released (Shen et al., 2012). This version contains fully thermo-mechanical and hydro-mechanical couplings. Over the years the code has been applied to a large number of different rock engineering problems.

Backers and Stephansson (2011) has recently completed modelling for SSM with the latest version of FRACOD containing coupled H-M and T-M processes. The code has been used for studying fracture initiation and propagation during the critical periods of the lifetime of a KBS-3V repository, in a way similarly to the work conducted by the authors of SKB TR-10-23 but just for one size of the models. The model geometry, boundary stresses and material parameters were extracted from SKB’s reports of the site descriptive model for Forsmark. The main conclusion of the work for SSM is that the risk of spalling in the deposition holes and fracture propagation in the near-field rock mass after excavation is minor or zero as long as the axis of the deposition tunnel is oriented parallel with the direction of the maximum principal stress. During the temperate period, fracture propagation and coalescence is rather common among the models studied with FRACOD. Severe fracture propagation together with fracture coalescence appears in all models subjected to the stress field presented by SKB in their site descriptive model for Forsmark. It is likely that the propagation and coalescence of new fractures will develop new path ways for the groundwater in the near-field. For certain parts of the near-field, a fluid path way from deposition holes to the adjacent tunnels is likely to develop.

In Section 3.2 about propagation and coalescence of existing fractures, SKB refers to a recent study by Damjanac and Fairhurst (2010) affirming that confinement suppresses time-dependent fracture growth since fracture growth requires tension at the fracture tips for propagating a fracture. The first part of the statement by Damjanac and Fairhurst (2010) about tensile conditions (Mode I) might be correct, but the second part of the statement is incorrect. Fracture propagation from a pre-existing discontinuity (microcrack, joint, sets of joints and faults of all scales) can take place in shear conditions (Mode II) and does not require an initiation from tension at the crack tips or a tensile crack. From theoretical studies and, experimental test results (Backers, 2005) and also by using acoustic emission (Zang et al. 2000), tensile cracks at the crack tips are favored at low confinement. At high confinement, as expected in the near-field of the deposition holes at Forsmark during the temperate period and glaciation, shear fracturing is the dominant mode of fracturing and tensile fracturing at the fracture tips are suppressed. Damjanac and Fairhurst (2010) also discuss the issue of stress corrosion due to strength degradation at the crack tip and claim that confinement suppresses time dependent fracture growth also for the case of zero fracture toughness which represents the limit state of time-dependent strength decay of a tensile crack. It is true that the swelling pressure from the high compacted bentonite counteracts spalling around the periphery of the deposition hole and can suppress time-dependent fracture growth. However, the pressure also increases the confining stress outside the spalling zone that enhances the probability of shear failure at the tips of the pre-existing discontinuities. In the compressed area outside the zone of spalling, failure and initial fracture propagation from the tips of pre-existing discontinuities are governed by shear mode of deformation and not tensile mode. Modelling fracture initiation and propagation around deposition holes with FRACOD also show that once the propagation of a fracture has started the mode of deformation can shift from shear to tensile and back to shear depending upon the orientation of the generated fracture with respect to the far-field stress state.

A recent fracture mechanics study conducted by Ko and Kemeny (2011) has shown that there is a time constant in the so-called “Charles’ law”, which determines the relationship between fracture growth velocity and fracture toughness of a material, and this is a true material parameter, independent of mode of fracturing (Mode I, Mode II) and Mode III in tearing). Therefore, the time-dependent strength degradation (stress corrosion) at the tip of the fracture is independent of the mode of fracturing. It is also known that the ability to fracture rock expressed by the fracture toughness is dependent on confinement (Backers, 2005). For a situation where mixed mode fracturing takes place, the tendency is that increasing confinement suppresses tensile mode (Model I) fracturing and promotes shear (Mode II) and tear (Mode III) fracturing. Since the time constant in Charles’ law is independent of failure mode, and therefore the argument used by Damjanac and Fairhurst (2010) and later by SKB that fracture growth requires tension at the tips of the propagating fracture is not valid. The stress state in the rock mass around the deposition holes is mainly compressive and therefore the fracture initiation and propagation is dominated by shear fracturing. The dominance of shear fracturing during fracture propagation can be observed in the many examples presented by Backers and Stephansson (2011).

At the end of Section 3.2, SKB claims that time-dependent fracture growth is a process that will be limited in both time and space and that it will not be important for the overall permeability of the repository. SKB has to prove this statement by modelling the fractured rock mass response to the different phases in the development of the repository over time. Such modelling also has to consider the geometry and properties of the Discrete Fracture Network (DFN). The modeling results presented by SKB do not consider the DFN in the near-field and the stability analyses are performed with elastic models without fractures using the code 3DEC.

Regarding the stress-transmissivity relationship, normal closure model due to normal stress is fitted by an exponential model with residual and maximum apertures (Eq. 3-7). This model fits reasonably well with the response predicted by measured parameters from cyclic loading in compression tests. Concerns and major comments are directed toward the shear dilation perceived in this report. It was stated in SKB's report that '…it is assumed that transmissivity increases, caused by shear displacement taking place under effective normal stress higher than around 6-7 MPa, are sufficiently small to be ignored". It is emphasized that this statement is an "hope-for-the-best" approach rather than being conservative. On the contrary, the magnitude of the shear dilation can still be significant under moderately high normal stress. The SKB report pointed that there are contradicting observation in Barton and Choubey (1977), Olsson (1998), Koyama (2007), and Esaki et al. (1999). Barton's model shows that the dilation angle can be meaningful even at moderate normal stress (5-25 MPa). However, SKB states that Barton's model is valid only at low normal stress. It is pointed out that there is no supporting argument provided. Furthermore, shear test conducted on samples taken from Forsmark show that the dilation angle matches with this empirical equation for dilation angles. The dilation angle under normal stress of 5 MPa and 20 MPa can reach more than 10 degrees and 5 degrees, respectively. Dilation angle of 5 degrees and 10 degrees correspond to 9% and 18% of normal opening with respect to the shear displacement, respectively. For example, when there is 2 mm displacement, there will be around 170 and 350 μm shear dilation for 5 MPa and 20 MPa, respectively. This laboratory experiment conducted by SKB contradicts its own modelling assumptions (Hökmark et al., 2010). A numerical study conducted by Park and Song (2009) showed that shear dilation can be affected by the magnitude of normal stress. It is true that shear dilation is a quantity that cannot be easily measured and it is hard to find records of field scale experiment. Because of this, it is not appropriate to ignore this shear dilation in the feasibility of Forsmark site.

Chapter 4 deals with data used in the THM modelling. More details about the input data for the modelling are presented in the Data Report. The layout used for the THM is the version with 13% loss of canister positions which gives the most concentrated thermal load. In the large-scale models every 8th canister is removed uniformly across the repository in order to achieve the given loss of canister positions. The repository is slightly inclined for drainage reasons in the tunnel system but the deposition area never reaches above elevation -450 m. For the modeling purpose the repository elevation -460 m has been selected. The orientation of the deposition tunnels varies between approximately 123° and 142° with respect to North. For the large-scale models SKB has been using the data from the stress model valid for domains FFM01 and FFM06 in Forsmark and presented for depth interval 400-600 m in the site descriptive model (SKB TR-08-05) and valid down to 1 km depth. This corresponds to a maximum and minimum horizontal stress of 40.1 MPa and 22.1 MPa, respectively and a vertical stress of 12.2 MPa at repository level. This has also been applied as the most likely stress data for the medium and small-scale models. For analyses of the potential of spalling SKB has performed the analyses with five different stress data sets where all sets of data except one have stress magnitudes larger than the most likely stress model.

The stress measurements conducted with hydraulic methods gave about half the magnitudes of horizontal stresses compared with the overcoring results. The potential low stress magnitudes in the horizontal direction are not likely to generate any spalling from excavation and most likely not from the temperate period. The Reader would like to know the rock mass response of the large scale and medium scale models for the glaciation period and how it relates to the modelling results from the high stress models. These results are missing in the report.

Chapter 5 describes the thermal evolution of the repository. A maximum peak buffer temperature below 100°C is the dimensional guideline for determining the spacing between canisters and deposition tunnels in the different rock domains of the repository. The tunnel spacing has been set to 40 m and the canister power to 1,700 W at the time of deposition. SKB has decided to use constant canister spacing within each of the two major rock domains at the Forsmark site. Canisters will not be placed in amphibolites within the two rock domains of the repository. The calculation of peak buffer temperature is presented in Section 5.3. In the section SKB presents the important equations for the temperature drop across the bentonite buffer for dry and wet holes. However, reference is missing and it needs to be presented.

In calculating the temperature drop across the buffer, the air-filled canister-bentonite gap gives a major contribution (cf. Fig. 5-3). What is the contribution in temperature from the gap filled with pellets between the buffer and rock? During SKB's site investigations major efforts were made to develop a probabilistic approach to the determination of thermal input data for design. In preparing the licence application, SKB has developed analytical expressions to determine the effective and dimensioning thermal conductivity of the rocks at Forsmark and from the results canister spacing at given peak buffer temperature for the two major rock domains in Forsmark has been calculated. Since the analytical solution does not account for spatial variations of the thermal properties SKB has introduced a temperature correction (Eq. 5-4). Considering the temperature correction that was also applied in the Site Engineering Report (SKB R-08-83), SKB reaches the conclusion that less than one canister have a peak buffer temperature larger than 95 degrees and about 98% of the canisters have a margin of 10°C or more (Fig. 5-7). This is an acceptable results and it shows that the selected margin of 5°C with respect to the design criteria of 100°C is appropriate.

The largest uncertainty about the thermal evolution is the heat transport properties in the interior of the deposition holes and in particular to the situation about dry or water saturated condition in the borehole. This uncertainty about thermal evolution is indirectly confirmed by the outcome of the CAPS experiment in Äspö HRL (Lönnqvist, 2008). The large variability of the spalling in the 8 heated boreholes in the floor of a tunnel at Äspö, with less spalling in the dry holes, reflects the variability in the heat transport properties in the interior of the deposition holes. SKB claims that uncertainties in rock thermal properties (conductivity, anisotropy and variability in measured data) have significantly smaller effects, between 1-2°C of the final temperature, compared to larger effect of dry condition in the deposition holes in the range between 3°C and 4°C. Finally, uncertainty related to SKB's assumption of simultaneous deposition of all canisters in the repository is estimated to be less than 0.1°C. The fact that SKB has applied both analytical methods and numerical models to the same problem of resolving the different aspects of the thermal evolution of the repository, there are high confidence in the estimated uncertainties presented by SKB. However, SKB needs to have a better understanding and clear design rules for assuring the final temperature of the engineer barriers as a function of rock mass saturation.

Min and Stephansson (2009) have conducted a modelling study for SSM about shear-induced fracture slip and permeability change in a repository using input data from the initial phase of the site investigations at Forsmark. They were using the COMSOL (2008) partial differential equation solver using the Finite Element Method to calculate the temperature distribution and stresses at the repository site. They used slightly different input parameters and repository geometry compared with the study presenter in SKB TR-10-23. The increase in temperature at selected areas, profiles and monitoring points in the repository and presented in Figs.11 through 14 in Min and Stephansson (2009), show striking similarities with the results presented in Figs. 5-11 through 5-16 in the SKB report. The somewhat higher temperatures with time for the first mentioned study is due to the repository geometry, and selected rock thermal properties. The good agreement between the SKB results and the modelling by Min and Stephansson (2009) gives additional confidence in the thermal calculations.

Chapter 6 is about the assessment of large-scale THM evolution during the thermal period of the repository. SKB has applied the analytical thermo-mechanical solution by Claesson and Probert (1996) to calculate the thermally induced stresses of the repository and the surroundings (Fig. 6-3). The repository area itself and an area ca 250 m above and below the repository are characterized by compressive stresses and the area about 200 m below the surface is a zone of tensile stress. The tensile stress at the ground surface reaches about 5 MPa after 500 years and about 10 MPa after 1000 years. The analytical solution in the SKB report and the modelling results with COMSOL by Min and Stephansson (2009) give close similarities although there are slightly different absolute values because of differences in parameter input and modelling sequences. This gives confidence about the thermo-mechanical stress development in the repository and its surrounding.

Using the 3DEC code, SKB calculated the effective normal stress along three vertical scanlines A, B and C across the repository and determined the normal and shear stress on all possible fracture plane orientations. Based on the stresses acting on the fractures, the factor of safety for slip assuming Mohr-Coulomb failure criterion was calculated for selected points along the scanlines. A friction angle of 35°.8 and cohesion 0.5 MPa were applied. SKB found that gentle dipping fractures are unstable with a safety factor less than 1.0. Based on the acting shear stress, the shear displacement according to Eqs. 6-1 and 6-2 could then be calculated along scanlines A and B to vary between 6 and 27 mm for the fractures and/or zones of a certain size. 3DEC models were also used to investigate and determine the boundary conditions for near-field models, stress evolution between repository and ground surface, heave of the ground surface, stress-induced transmissivity variations at different locations within the repository region and finally the potential for shearing and a qualitative assessment of the impact of shearing on transmissivity.
The slip estimates in SKB's analysis are made by using an analytical elastic solution for the shear displacement at the centre of a circular fracture with a given radius. Notice that the equations presented for the shear displacement (Eqs. 6-1 and 6-2) were calculated for a continuum medium and the actual stress distribution in discontinuum medium can be different. Although 3DEC was extensively used in this SKB report, only few modeling explicitly considered the fractures. This leaves an impression that the full capability of 3DEC was not used in this report.

It is suggested that the thermally induced shear stresses are small compared to the total stress components (sum of thermal and in situ stress) and therefore it was assumed by SKB that the principal stress during the thermal phase have the same orientation as the in situ principal stresses. However, it is noted that this is not the case especially near the corner or sides of the repository. A recent study by Min and Stephansson for SSM (2009) showed that the magnitude of thermal shear stress can reach up to 2 MPa, which is not negligible.

In the SB report the possibility of shear slip at the existing fractures was presented on stereonet in terms of effective normal stress and factor of safety defined as the ratio between shear strength and the shear stress. Average values of the orientation of the four global sets in fracture domain FFM01 were also plotted for comparison (Fig. 6-24 through 6.26). Obviously these plots are one way to show the possibility of shear slip for the existing fractures. However, it is pointed out that the fracture orientation exists with wide variability and it is more appropriate to take into account the expected distribution of orientations. This is especially the case when the shearing potential of a fracture is considered in view of transmissivity change, where only a portion of the fracture is responsible for the entire fluid flow.

Concerning the relative transmissivity, SKB claims that the transmissivity will increase with a factor 2 for horizontal fractures that pass through the repository. Vertical fractures striking perpendicular to the least horizontal stress direction (i.e. striking 145°) show a transmissivity increase with a factor 2.5 above the heated deposition areas. In a 3DEC analysis of the large gently dipping zone ZFMA2, SKB found that the normal stress increases across the deformation zone and that the relative transmissivity is reduced except for the shallow parts. Three of the five sets of major deformation zones at Forsmark are steeply dipping and the remaining two sets are horizontal to sub-horizontal (see Figs. 4-5 and 4-7 in the SKB report). In addition, two of the sets are strikingly parallel with the direction of the maximum horizontal stress. The geometry of the discontinuities results in a very stable rock mass geometry with respect to fault reactivation and slip caused by the in-situ stress field at the site and thermal stress, except for the gently dipping fractures. Therefore, the calculated slip displacements and transmissivity changes of the major deformation zones are minor during the thermal phase.

Min and Stephansson (2009) and Lee, Min and Stephansson (2012) used another approach to analyse shear-induced fracture slip and permeability change. After analysing the thermally induced stresses by using COMSOL they applied Coulomb failure criterion with zero cohesion to determine likely areas with slip in the repository and its surroundings for the case of effective and total state of stress. Fracture orientations were then generated by Latin Hypercube Sampling (Mckay et al., 1979) and the probability of fracture shear slip was calculated with respect to the time. Also, the Authors considered the stress state at the surface above the centre of the repository where tensile stresses will develop as the most critical area for failure and slip of the rock mass.

Unlike SKB, Min and Stephansson (2009) used the discrete fracture network (DFN) from Forsmark site and applied the calculated thermal stresses to the DFN models and thereafter applied the discrete element method code UDEC (Itasca, 2000) and calculated the permeability changes. Four out of six DFN models showed permeability reduction due to normal closure. The other two models showed shear slip and a permeability increase with a factor of up to four, which is explained by shear dilation as demonstrated by Min et al. (2004). After a time scale of 10,000 years the models showing shear slip resulted in irreversibility of the permeability through the modelling of unloading during the cooling phase. The DFN-DEM analysis of shear slip and permeability change of the DFN from Forsmark resulted in larger permeability changes compared with the analysis conducted by SKB. Also, the stress state close to the surface above the repository area was found to be the most critical and the permeability change from shear induced slip resulted in irreversible permeability change. Because the study by Min and Stephansson (2009) considered only a few selected points around repository and effect of tensile stress was not applied in discontinuum model, it has a certain limitation in assessing overall behavior of the repository. The three issues about thermally-induced shear slip, effect of tensile stresses at the surface above the repository and irreversible permeability need further analyses at different scale for the repository at Forsmark.

Chapter 7 presents the large-scale THM evolution during glacial phase. Recently, SKB has presented major improvements of modelling the glacial phase of the repository development with time (SKB TR-09-15). The magnitude of the glacially induced pore pressure is of utmost importance for the stability and transmissivity of the fractures and the risk of hydraulic jacking – a phenomenon of opening of fracture due to elevated hydraulic pressure – at the site. SKB has not made any coupled THM simulations of this problem and they have used hypothetical fracture planes with orientation perpendicular to the major principal stresses. Two different stress-transmissivity models have been applied to describe the relative transmissivity as a function of normal stress variation. SKB has access to computer codes (e.g. ABAQUS) to simulate the fully coupled THM process from a glacial cycle with more realistic fractures and parameter for the hydro-mechanical coupling. The THM modelling of the large-scale evolution during glaciation, including permafrost and the crust/mantle system, can all be performed with the ABAQUS code. The selected five time spots picked during the glacial cycle are relevant and critical stages and should be maintained in further modelling work.

Furthermore, Chapter 7 shows the shear displacement and transmissivity changes during the THM evolution of the near-field fractures in the vicinity of the deposition holes and tunnels. SKB has applied the same approach about normal stress influence on fracture transmissivity as for the large-scale models. The medium-sized near-field models have the size 200 m × 200 m × 200 m and are intersected by five fractures with a radius of 50 m. In 3DEC all fractures are through-going the model so the area outside the 50 m radius of the fracture is given high strength and low deformability. The boundary stresses for the models are taken from the global models. Four different repository phases have been analysed: i) operational, ii) temperate, iii) glacial and iv) permafrost. SKB has found that the maximum shear displacement of the fractures is at maximum 8-9 mm. The change in transmissivity is concentrated to a limited region around the tunnel. At distances larger than 2 m away from the tunnel there are small changes in the relative transmissivity.

SKB has spent a large amount of time and efforts on developing the fracture network models of the rock mass at repository level in Forsmark. One would expect to find some of these models used in the assessment of the potential shearing and relative permeability during the critical phases of the repository. This comment is particularly relevant for the THM analysis of the medium sized near-field models. SKB has taken the approach to use a fixed number of fractures and located the fractures so that some of them intersect the tunnel and deposition hole and so that one fracture is oriented parallel with the tunnel axis. The centre of the circular fracture lies on the axis of the tunnel or deposition hole. Fractures are assumed to have no friction and are open within the 50 m radius. This is very conservative assumption of fracture geometry. Despite the conservative approach in SKB's fracture geometry the change in normal stress across the fractures and the transmissivity change are found to be very small. It remains for SKB to prove that the presented results are valid for more realistic fracture networks, and data on the normal stress variations and related transmissivity changes. The parameter values used in the modelling are derived from laboratory tests on small samples and applied here to large structures with fracture surfaces being far from perfectly planar and continuous. The major concern is the rock down to a depth of 200 m above the repository where tensile stresses are acting. This is also the area where pre-existent sheeting jointing (i.e. exfoliation joints) appears down to the depth where the tensile stress starts to develop in the late stage of the temperate phase. Additional studies are needed to understand how the rock mass above the repository will respond to the thermal load at the late stage of the temperate period.

The modelling methodology in Chapter 8 for the medium-scale THM evolution needs to be made clearer. It appears that the medium-sized near-field model with dimension of 200 m × 200 m × 200 m addresses explicit modelling of the deposition tunnels but not of the deposition holes. Although explicit modelling of all the deposition holes may be not necessary, assumption of not considering deposition holes needs to be explained. In each location where deposition hole is supposed to be placed, thermal sources were generated. Why does the Figure 8-7 show non-uniform temperature distribution? After 100 years, the temperatures near the heat sources should be at least higher than 45°C.More explanation on this figure is necessary as this is critical in evaluating the following modelling results about the thermal stress and its effect on shear displacement.

In Chapter 9, SKB has assessed the spalling potential in the deposition holes of the repository. In previous studies by SKB, Hökmark and Fälth (2006) could show that stress reductions of 15% and/or stress accumulations up to ca 50% can develop around the deposition hole once fractures are simulated in the models about spalling. With this knowledge SKB has decided to use elastic models in assessing the spalling potential in the near-field. This is an acceptable approach considering the sparsely fractured rock at repository level in Forsmark. However, SKB is recommended to perform a series of models of spalling considering typical fracture networks from the DFN studies. This will give SKB a better knowledge about the variability of stress concentrations and spalling in the deposition holes and will assist SKB in mitigating the spalling.

SKB has selected six different locations evenly distributed within the area of the Layout D2 at Forsmark for near-field thermo-mechanical modelling. The potential for spalling in the deposition holes and roof of the tunnel has been studied for operational, temperate and glacial phases of the repository. Displacement boundary conditions with data from the large-scale models were used for analysing the temperate phase. For the glacial phase the stresses from ice load are added to the in-situ rock stresses. A spalling strength of 52-62 % of uniaxial compression strength (UCS) of the intact rock and different orientation of major horizontal stress with respect to tunnel axis has been used to evaluate the results of the modelling. The maximum stress appears in the deposition hole close to the Central Area of the repository. The excavation of the deposition hole does not create spalling if the axis of the deposition tunnel coincides about with the direction of the maximum horizontal stress. The same result is obtained in the fracture mechanics analysis with FRACOD (Backers and Stephansson, 2011).

SKB has found that after 50 years of heating, severe spalling appears and this is further increased to develop along the full depth of the deposition hole for the proposed maximum in-situ stress model with maximum horizontal stress exceeding 60 MPa. The spalling strength is most likely exceeded down to the mid-height of the deposition hole during the temperate period given the mean virgin stress magnitudes suggested by SKB. Spalling is not of major importance during the glacial period. The additional loading is directed vertically and the full swelling pressure from the bentonite would prevent spalling unless significant drainage of bentonite due to piping erosion occurs. The impact of the event of bentonite erosion was not thoroughly investigated in this review report, and this merits further examination during the main review phase.

SKB's study of the spalling potential in the deposition holes illustrates the importance of valid magnitude and orientation of the in-situ stress field for assessing spalling at the site in Forsmark. The stress measurement results presented by SKB for Forsmark are not conclusive. The applied hydraulic and overcoring relief methods had problems and gave different results of the stress magnitudes. Furthermore, old overcoring rock stress data outside the Target Area had to be used for determining the stress model for the site. The present situation about the knowledge about the stresses at depth in Forsmark means that SKB has to determine the stress state during the excavation of the Access Tunnel and Central Area. First when the stress state at depth in Forsmark is established and confirmed a proper assessment of spalling during different phases of the repository can be made.

The largest uncertainty about the thermal evolution is the heat transport properties in the interior of the deposition holes and in particular for dry or water-saturated condition in the deposition hole. The uncertainty about thermal evolution is indirectly confirmed by the outcome of the CAPS experiment in Äspö HRL (Lönnqvist et al., 2008) where dry boreholes show less spalling.

SKB has applied both analytical and numerical methods for resolving the different aspects of the thermal evolution of the repository. There is very good agreement between modelling and analytical results which gives high confidence to the presented results. However, SKB needs to have a better understanding and clear design rules for determining final temperature of the engineer barriers as a function of rock mass saturation. SKB also has to solve the problem resulting from conducting thermal testing on water saturated rock samples to be used for the design of canister spacing with the assumption of dry deposition holes.

The Discrete Fracture Network (DFN)-Discrete Element Method (DEM) analyses by Min and Stephansson (2009) of shear slip and permeability change of the Discrete Fracture Network from Forsmark resulted in larger permeability changes compared with the analysis conducted by SKB. It is noted that this observation was possible only when explicit hydraulic calculation in DFN was conducted due to the connectivity and channeled fluid flow. Also, the stress state close to the surface above the repository area was found to be the most critical and the permeability change caused by shear induced slip resulted in irreversible permeability change. The three issues about shear-induced permeability, effect of tensile stresses at the surface above the repository and irreversible permeability conditions following the temperate phase need further analyses at different scales for the repository at Forsmark using direct calculation of coupled hydromechanical process in DFN.

6.3. Minor and editorial comments

In Section 2.2.2, SKB describes the principles of THM coupling in jointed rock mass. The general principles of THM coupling is a two-way coupling between pairs of individual processes. The water buoyancy from the heating of the groundwater and the convection of the groundwater causing changes in the temperature are omitted in the 3DEC modelling. Since the buoyancy and convection are known to have a small effect on the performance and safety of the repository, the H-T and T-H couplings can be omitted. Similarly, the one-way coupling of the effect of mechanical processes on temperature caused by friction can be omitted in the modelling of the repository. Hence, the coupling processes considered in SKB modelling is adequate.

Verification of a chosen numerical code is a prerequisite for further application in order to confirm that the equations (typically partial differential equations) treated in numerical method is being solved correctly. In this sense, the very good agreement between analytical solutions and modelling with the Code-Bright models for the pore pressure at different stages of ice cover and retreat of the ice margin for different hydraulic diffusivity presented in Appendix D of the report gives confidence to the presented pore pressure calculation at different periods of glaciation and deglaciation. Application of a pore pressure of 25 MPa for an ice thickness of 2.8 km seems realistic considering the applied hydraulic diffusivity.

In Section 3.3, SKB is discussing the approach to evaluate the modelling results related to spalling, i.e. the stress-driven instability generating loose pieces of rock material in the direction of least horizontal stress around the borehole. SKB intends to fill the gap between the compacted bentonite rings and the wall of the dry deposition hole with bentonite pellets. The temperature from the waste will soon increase after deposition and swelling of the pellets will be limited. SKB’s conclusion not to trust support pressure from the bentonite pellets during the temperate period is relevant.

In the TASQ tunnel at Äspö HRL, SKB conducted the APSE project and found that the spalling strength should be about 57% of the uniaxial compressive strength (UCS) of the intact rock (Andersson, 2007). This value also corresponds to the crack initiation value for the Äspö diorite. One has to remember that the experimental set up and the stress path generated in the APSE project is different from the stress path and overall conditions for a KBS-3V repository concept. Therefore, SKB has to wait for additional data from the prototype repository experiments or other field tests to gain confidence in the selected value 57% of UCS for the onset of spalling in the application to the conditions at Forsmark. SKB has conducted a simple heater test in the field at Forsmark (Sundberg et al., 2007) but nothing is mentioned about the results and the likelihood for spalling in the report TR-10-23. Results from the field test at Forsmark (SKB P-07-104) gave an anisotropy of thermal conductivity of 1.15 while laboratory measurements resulted in a value of 1.40. SKB has to explain the difference and decide about the method to determine the values to be applied in the design work.

The observations of spalling in the boreholes of the CAPS experiments in the TASQ tunnel at Äspö HRL gave additional and valuable information. The dry holes with diameter 0.5 m gave short and minor spalling in separated regions. In wet boreholes continuous zones of failure were observed. Hence, it is likely that the degree of saturation and suction in the rock mass, in addition to the type and orientation of primary structures, also play a role in assessing the potential for spalling. From the observations in the CAPS experiments, SKB draws the conclusion that the threshold for spalling in dry boreholes (57% of UCS) is likely to be underestimated. In Section 3.5, summary of the evaluation approach, SKB claims that the spalling strength can be assumed to be 52-62% of the UCS determined in laboratory. The somewhat unclear situation regarding the influence of water, temperature and primary rock structure on spalling performance in the deposition holes shows that SKB has to plan for extensive heater tests at depth in the facility in Forsmark. Additional study will provide a more confidence in understanding the spalling behavior around the deposition hole and this study is necessary because the spalling strength observed at TASQ tunnel may not be applicable to the Forsmark site. Various continuum and discontinuum modeling tools available today can then be employed to confirm the ability of predicting the spalling behaviour.

The presentation in report TR-10-23 about transmissivity change caused by normal stress variation is based on the empirical relationship by Barton (1982). It states that the hydraulic aperture is related to the joint roughness coefficient (JRC) in power 2.5 over the ratio of mechanical and hydraulic aperture in square. Based on Barton's equation and the continuously yielding model in the distinct element codes by Itasca (2006) and the model suggested by Liu et al. (2003), the Authors derive a relationship between the mechanical and hydraulic aperture as a function of normal stress (Eqs. 3-6 and 3-7 in SKB TR-10-23). From the empirical relationships for mechanical and hydraulic aperture (Eqs. 3-6 and 3-4), the Authors present simplified exponential fits for two different parameter sets of fractures where the parameters are taken from the Data Report (SKB, 2010). The relative transmissivity of the fractures is governed by the aperture changes in cube and/or the stress ratio between initial and final stress in the models. The same approach as described here was used in the SR-Can report. The description of normal mechanical behaviour adopted in this report can be well accepted in the scientific community except the fact that the role of chemical reaction in the fracture such as precipitation and dissolution was not considered. Although this aspect merits significant investigation, it is outside of the scope of this review.

In Section 4.5, SKB presents data about fractures and fracture zones for the modelling work in different scales. For the large-scale modelling work deformation zones are not explicitly simulated. Instead hypothetical fracture planes oriented perpendicular to the direction of in-situ stress components (vertical and horizontal planes through the models) are simulated in the models. This approach is somewhat artificial and the present capacity of the 3DEC code should be able to handle all the major deformation zones in a global model. Such a global 3DEC model with deformation zones included was generated by Hakami (2006) in studying the spatial variation of the in situ stress field at Forsmark. The glacial scenario and the input parameters and boundary conditions for Forsmark are extracted from the report by Lund et al. (2009), Hartikainen et al. (2010) and they are also presented in the Data Report (SKB TR-10-52). A similar modelling strategy could have been applied to the models with different scale presented in SKB TR-10-23.

The glacially induced principal stress magnitudes and orientation of principal stress components for the depth down to 1 km are very much dependent upon the estimation of the global stress field in Fennoscandia. This is one of the major uncertainties in simulating the rock mass response to the THM processes at different periods of the repository.

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APPENDIX 1

Coverage of SKB reports

Table 1: List of reviewed SKB reports and sections.

Reviewed report	Reviewed sections	Comments
[SKB TR-11-01 SR-Site main report]	[Chapter 4, 7.4.5, 8.3.4, 10.2.1, 10.2.2, 10.3.4, 10.3.5, 10.4.4, 14.4.6, 15.5.12, 15.5.13, 15.6.1, 15.6.7 and 15.7.4]	
[SKB TR-10-48 Geosphere process report]	Section 2 and Section 4	
[SKB TR-10-52 Data report]	Section1, Section 2 and Section 6	
[SKB TR-10-23 THM-issues in repository rock, Thermal, mechanical, thermo-mechanical and hydro-mechanical evolution of the rock at the Forsmark and Laxemar sites]	All Sections	

APPENDIX 2

Suggested needs for complementary information from SKB

1. [SKB TR-11-01, p.116] SKB is suggesting the new idea that sedimentary loading is a process that besides tectonics gave rise to the build-up of high rock stress in the bedrock. Has SKB conducted any mathematical modelling to illustrate the suggested processes for reactivation of gentle dipping fracture zones and generation of sheet joints?
2. [SKB TR-11-01, in Section 7.4.5 Geosphere, Table 7-6 Process Table, Process Ge1, Heat transport] SKB claims that heat generation from the waste during excavation/operation can be neglected. Has SKB studied the case of a leaking canister in the deposition tunnel during emplacement? If the clean-up takes a long time the heat development in adjacent deposition hole can raise the temperature and prevent additional deposition and backfilling.
3. [SKB TR-11-01] SKB claims that generation of earthquake due to heat transport is not relevant. Has SKB performed any mathematical modelling to demonstrate that thermally induced generation of earthquakes and its potential hazard to the nuclear reactor is not relevant?
4. [SKB TR-11-01, Section 15.5.12, about selecting deposition holes – mechanical stability] SKB describes the design criteria for placing the canisters in the vicinity of 3 km long deformation zones and the EFPC criteria. As such, the condition for reducing the respect distance is not clear and SKB need to provide a specific condition to reduce the respect distance to large deformation zones?
5. [SKB TR-11-01 In order to develop the rock stress model, SKB is using old stress measurement results derived from the two boreholes DBT1 and DBT3 drilled in conjunction with the construction of the third power plant at Forsmark. These boreholes are located outside the target and candidate areas in other rock types and the measurements were conducted with the prototype of the Borre probe. Are the presented results from the two boreholes at all relevant for the stress model of the target area?
6. [SKB TR-10-52, Section 1.2.2] It is not clear from reading this section why SKB has decided to present two different approaches for selecting data and performing the safety analysis. Radionuclide transport is a part of AMF like many of the other processes why is this part treated separate and analysed with two different approaches?
7. [SKB TR-10-52, Table 2-4] Comparing the information in Table 2-4 with the two flow charts the following questions are raised: Why is Rock Mechanics (DR 6.4) omitted in AMF 2 flowchart? Why is the white box Layout D2 presented in flowchart AMF 2 omitted in AMF 1? Where is excess pressure from bentonite freezing considered in AMF 2?

8. [SKB TR-10-23, Section 2.6] This section is about glaciation and stress impact from the ice load. At the end of the section dealing with the stress impact from ice load, SKB claims that the impact of the basal drag is likely to be smaller than 1 MPa at the ground surface. Furthermore, the impact at larger depths would be well below this level and well below the weight of the ice sheet and the horizontal bending stress. It is not clear from reading the report if this bending stress is caused by the forebulge from the ice load or another mechanism.
9. [TR-10-23, Chapter 8] Modelling methodology in Chapter 8 medium-scale THM evolution seems to be presented more clearly. It appears that medium-sized near-field model has dimension of 200 m × 200 m × 200 m with explicit modelling of deposition tunnel but not deposition hole. In each location where deposition hole is supposed to be placed, thermal sources were generated. Why does the Figure 8-7 show non-uniform temperature distribution? After 100 years, the temperatures near heat sources are being generated and should be at least higher than 45°C as shown in the same report (e.g., in Figure 5-13). Additional explanation of this figure is necessary as this is critical in evaluating the following modelling results about the thermal stress and its effect on shear displacement.

APPENDIX 3

Suggested review topics for SSM

Followings are suggested review topics and first draft proposals of three Topics related to rock mechanics modelling related to long-term site evolution:

1. [Topic 1: Effect of thermo-shearing on the long-term performance of geological repository]
2. [Topic 2: Numerical analysis of seismicity induced by thermal stresses at Forsmark]
3. [Topic 3: THM coupling and fracture network evolution investigated by fracture mechanics approach]

Topic 1.

Effect of thermo-shearing on the long-term performance of geological repository

1. Background

Various studies have shown that shear displacement and dilation of fractures can be sources of mechanical instability and significant fluid flow in fractured rock. Thermal stress generated from heat-generating nuclear waste are on the order of up to 20 MPa and this can alter the stress state around a repository, and hence rock mass permeability. While the effect of excavation is expected to be produced in near-field, being defined as within a few times of the repository tunnel, the influence of thermal stress will reach mid- and far-field, which can be a few hundred meters from the peripheries of a repository. A field investigation by Barton et al. (1995) supports that critically-stressed fractures are for the ones carrying a major portion of the fluid flow and a similar finding was numerically demonstrated by Min et al. (2004) as shown in Figure 1. In a deep geological repository, heat is emitted by the nuclear waste and thermal stress is generated due to the confined nature of the rock as shown in Fig. 2. This can be a source of shear slip and dilation in the geological repository (Min and Stephansson, 2009).

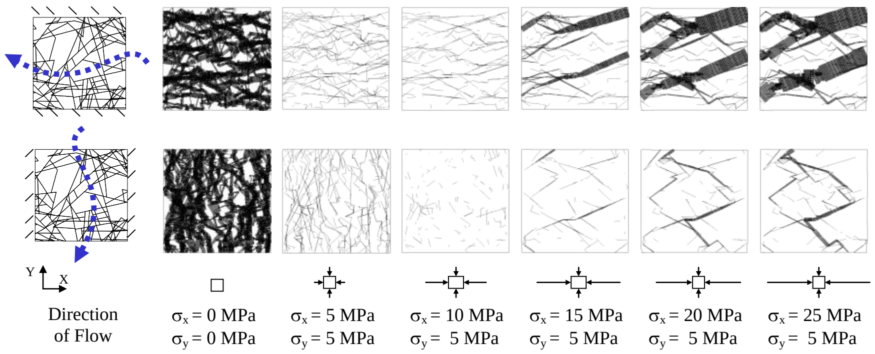


Figure 1. Enhanced fluid flow due to shear slip from the increased horizontal stress (Min et al., 2004). Shear dilation caused the increase of permeability by a factor of six when the range of allowable change of aperture was from 5 micron to 50 micron. The study was conducted in two dimensional plane strain condition.

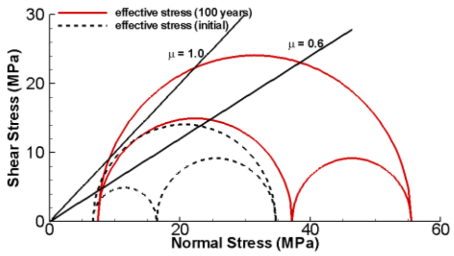


Figure 2. Changes of the stress state of after 100 years due to thermal stress (Min and Stephansson, 2009).

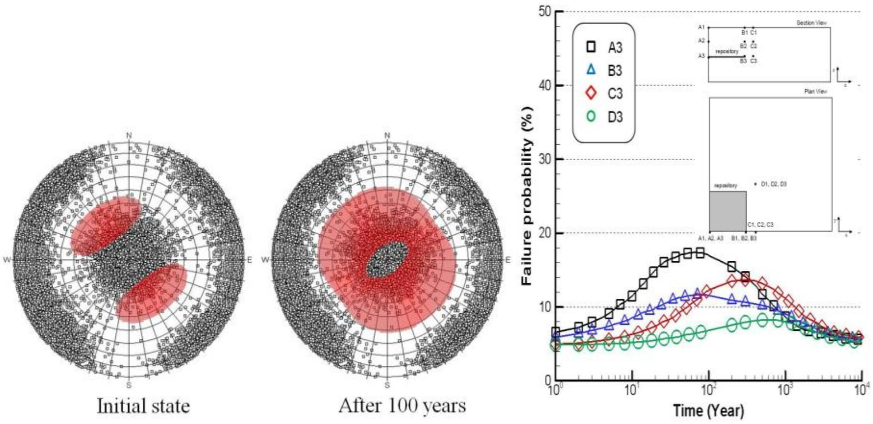
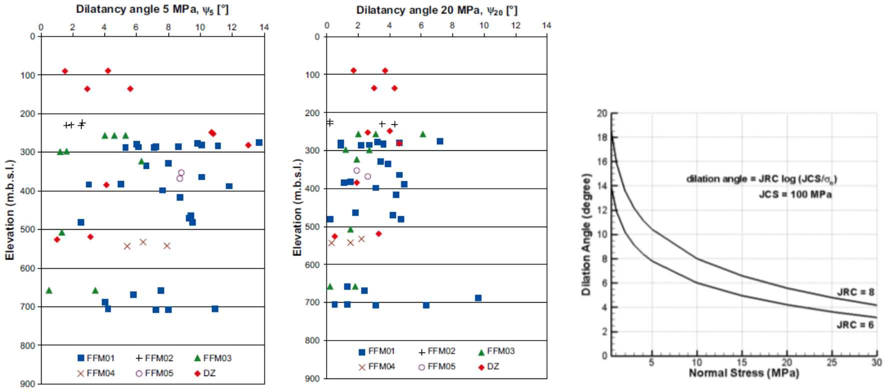


Figure 3. (a) Shear slip potential map and generated fracture pole, (b) probability of fracture shear slip at Forsmark site during thermal loading history. Locations are at the repository depth (Min et al., 2012).

Figure 3 shows the preliminary results of probabilistic analysis of shear slip potential. The results show that the fractures at Forsmark can have up to a 20% probability of failure and shear with the expected thermal stress.
Therefore, thermo-shearing, which is a phenomenon of shear displacement and dilation of fractures due to thermal loading, is an important mechanism to be studied for the safe disposal of nuclear waste in deep underground repositories. The permeability change associated with thermo-shearing is also expected to affect the fluid flow pattern in deep underground and this is especially important since the increased permeability due to shear dilation may not be reversible. The candidate site at Forsmark proposed by SKB indicates a high stress ratio (ratio of major principal stress to minor principal stress) and this implies that many fractures in the sites are critically or nearly-critically stressed under the current stress state (SKB, 2011). This means that even a slight change of stress can trigger a shear slip as shown in Figure 2. Furthermore, sparsely fractured rock at Forsmark will show relatively stiffer elastic modulus and this will induce higher thermal stress.

2. Motivation for independent review

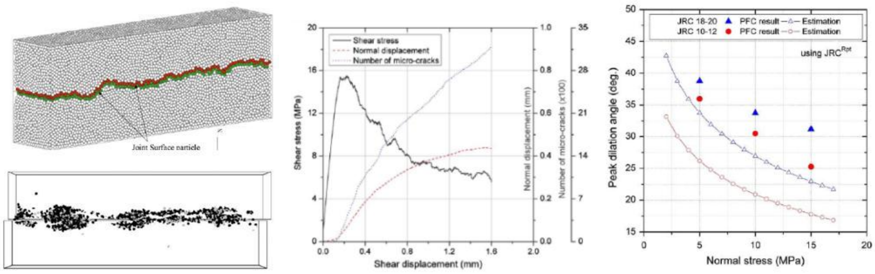
In this initial review phase it was found that SKB ignored shear-induced permeability changes under moderate normal stress of larger than 5 MPa (Hökmark et al., 2010). However, experimental and numerical studies support that up to two orders of magnitude change of permeability is expected under normal stress of up to 20 MPa. Figure 4 shows the dilation angle obtained from the laboratory test on fracture samples taken from Forsmark and the empirical equation for dilation angles. The dilation angle under normal stress of 5 MPa and 20 MPa can reach more than 10 degrees and 5 degrees, respectively. Laboratory results on rock samples from Forsmark agree reasonably well with existing empirical results (Figue 4, (c)). Dilation angles of 5 degrees and 10 degrees correspond to 9% and 18% of normal opening with respect to the shear displacement, respectively. For example, when there is 2 mm displacement, there will be around 170 and 350 μm shear dilation for 5 and 20 MPa, respectively. This laboratory experiment conducted by SKB contradicts its own modelling assumptions (Hökmark et al., 2010).



(a) (b) (c)

Figure 4. Dilation angle from the laboratory test on fracture samples taken at Forsmark (Glamheden et al, 2007) (a) & (b), and empirical equation (c) (Barton and Choubey, 1977).

A numerical study conducted by Park and Song using Particle Flow code (2009) showed that shear dilation can be affected by the magnitude of normal stress. Although the shear dilation decreases with increasing normal stress, the magnitude of shear dilation is still significant enough to be considered in this numerical study where constant normal stress was applied for the boundary condition. Figure 5 shows the layout of the numerical test (Figure 5, (a)) and it shows that normal dilation can be up to 400 μm with shear displacement of 1.6 mm under a normal stress of 15 MPa (Fig. 5(b)). This numerical study was validated by achieving a reasonable agreement between the obtained shear strength under various Joint Roughness Coefficients (JRC) and the one calculated by Barton's model. This also indicates that the existing empirical equation under various normal stress boundary conditions may underestimate shear dilation (Figure 5(c)).



(a) (b) (c)

Figure 5. Numerical simulation of a single-fracture dilation (Park and Song, 2009). (a) single fracture layout, (b) shear stress-shear displacement-normal displacement relationship, (c) normal stress-peak dilation.

Figure 6 shows the permeability evolution during a thermal loading cycle. Notably the elevated permeability at around 100 years did not recover to the initial state and even underwent an increase. The observation is due to the irreversible process of shear dilation and a further reduction of normal stress across the fracture. This observation merits further systematic investigation.

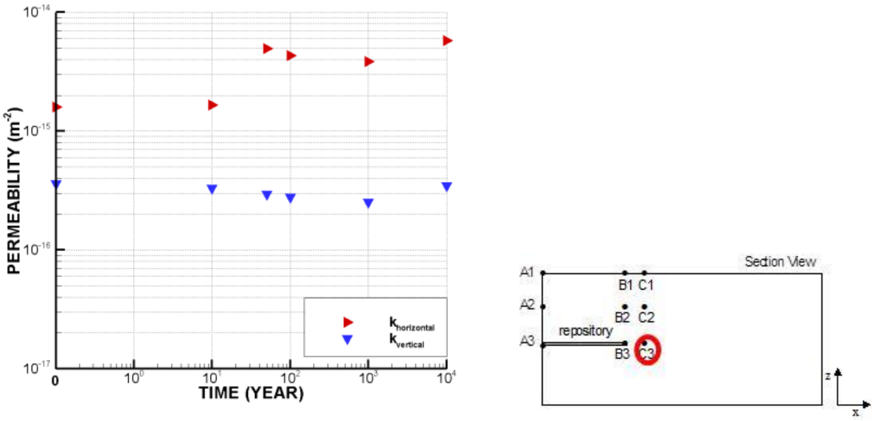


Figure 6. Permeability evolution during thermal loading cycle (Min and Stephansson, 2009). Permeability increased before 100 years by a factor of three due to shear dilation during heating phase and the increased permeability never recovered to initial state due to the irreversible shear dilation. Rather the final permeability increased due to the normal opening of fracture during cooling phase.

In SKB's study on THM issues (Hökmark et al., 2010), the possibility of shear slip at existing fractures was presented in stereonet in terms of effective normal stress and the safety factor was defined as the ratio between shear strength and the shear stress. The means of the four global sets fracture orientation were also plotted for comparison (Figure 6-24, 6.25 and 6.26 in Hökmark et al., 2010). It is emphasized here that fracture orientation exists with wide variability and it is more appropriate to take into account the distribution of orientation as shown in Figure 3.

3. Scope of the work

This study intends to tackle technical issues that were not covered in sufficient detail by SKB in the license application. Following is the list of tasks that would be performed for the independent study:

1. Task 1. Literature review on the shear dilation of fractures in laboratory and in-situ scale under moderate normal stress (5 to 25 MPa)
   a) Investigation of previous experimental and numerical studies on fracture shear dilation with special focus on the effects of normal stress
   b) Upscaling of laboratory study to in-situ scale with an emphasis on the geological repository at Forsmark.

2. Task 2. Thermo-shearing on medium-field repository performance during a thermal loading cycle
   a) Shear slip potential investigated by probabilistic analysis
   b) Thermo-shearing in a sparsely-fractured repository investigated by discontinuum thermo-mechanical analysis
   c) Significance of irreversible permeability change during cooling phase.

Task 1 deals with a literature review of the existing knowledge about shear dilation in a fracture under moderate normal stress. Although SKB's licence application did conduct a literature review and cited several important studies (Fransson, 2009), it

missed a number of key publications relevant to this topic and this resulted in an underestimation of the role of shear dilation.
Furthermore, fracture behaviour is highly scale-dependent and upscaling from the laboratory scale to an in-situ scale of up to a few hundred meters is crucial in estimating the effects of shear dilation.

Task 2 would focus on actual modelling of thermally-induced shearing, hence thermo-shearing, of fractures around the repository. This task is comprised of three key components: i) shear slip potential by probabilistic analysis, ii) thermo-shearing due to thermal stress and iii) irreversibility of permeability during the cooling phase. Shear slip probability will be determined based on the continuum thermo-mechanical analysis and discrete fracture network (DFN) statistics. This study, which will be conducted by implicit consideration of fracture network, will reveal the probability of shear slip of DFN at given stress state around the repository. This type of study (Lee et al., 2012) is being developed at Seoul National University (South Korea) and can be applied for SSM's Main Review Phase. The final product of this sub-task is a complete map of shear slip potential around the repository.

Thermo-shearing analysis will be conducted by a discrete element method. The study, which will be conducted by explicit consideration of fractures, overcomes the limitation of SKB's work, which only used an elastic thermo-mechanical calculation and neglected shear dilation. While a previous independent study by Min and Stephansson (2009) used a combination of continuum thermo-mechanical analysis and a Discrete Element Method (DEM), this study will be using both a combined approach and direct application of DEM (UDEC or 3DEC). This approach will give a more realistic estimation of thermo-shearing.

The third component of the Task 2 is concerned with the aspect of irreversibility of permeability during cooling. This aspect was completely ignored by SKB and it was partially dealt with by Min and Stephansson (2009). For dilated fractures under high normal stress, a further increase of permeability is anticipated contrary to the usual expectation of permeability recovery. The increase of permeability is caused by the increased normal displacement due to reduction of stress.

In addition to these three components, various issues such as the role of tensile stress build-up from the surface down to around 200 m and the significance of the anisotropic thermal conductivity will be investigated.
Figure 6 shows the key mechanisms and methodology for the proposed independent study.

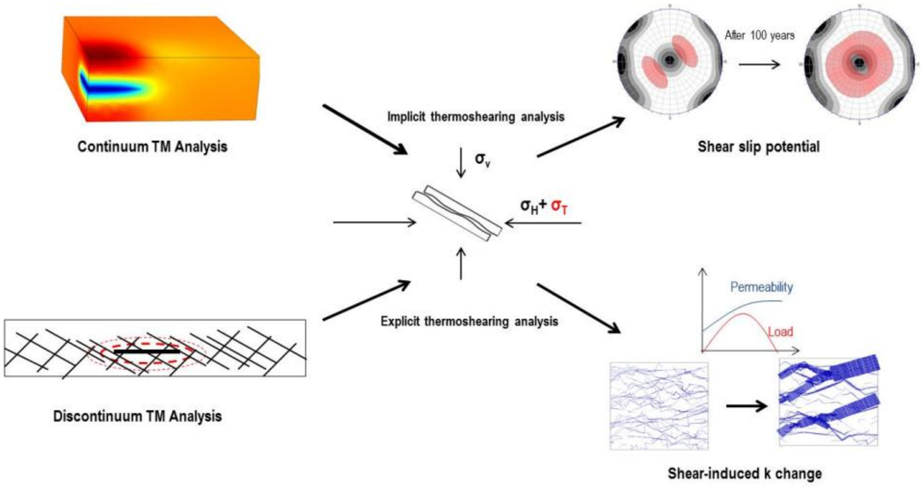


Figure 6. Key mechanisms and methodology for the proposed SSM's independent study.

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Topic 2.

Particle Flow Code 2D modelling of induced seismicity and related displacement by thermal-mechanical coupled processes for a deep geological repository at Forsmark

1. Background and objective

Deep geological disposal of spent nuclear fuel generates transient heat in the rock mass and the heat conduction leads to thermal expansion in the bedrock. The expansion and later cooling and contraction of the bedrock modify the stress state in both the near-field and far-field of the repository. The thermally induced stresses are superimposed on the in-situ rock stresses and the modified stresses from excavation and swelling pressure of the buffer and backfill. Motivation for this study is that SKB has not considered thermally induced seismicity from the spent fuel in SR-Site.

The aim of this study is to investigate: i) the local magnitude of thermally induced seismicity, ii) the risk of shear displacement of pre-existing faults and fractures in the near- and far-field of the repository and iii) the seismic hazard for the nuclear power units at the ground surface at Forsmark.

2. Numerical methods

The numerical tool proposed is discrete element model based Particle Flow Code 2D (PFC2D) from Itasca (Potyondy & Cundall, 2004). Thermo-mechanical coupled processes are modelled by using the PFC2D thermal analysis module which enables modelling of transient heat conduction and storage in bedrock and development of thermally induced displacements and strains as forces and stresses. Details of the thermal logic and how it is applied to Rock Mechanics modelling are presented by Itasca CG (2008) and Wanne and Young (2008), respectively.

Upon material failure, i.e. bond breakage in PFC2D, stored strain energy at the bond is released as kinetic energy in the form of a seismic wave. Seismic waves that initiate at a point of crack and propagate across the model are captured by using the seismic monitoring scheme (Hazzard and Young, 2002) and seismic information, e.g. moment tensor, magnitude, etc. are calculated. More details on this numerical seismic monitoring technique are given in Hazzard and Young (2000; 2002; 2004). Recently, Yoon et al. (2012a) applied this numerical scheme in PFC2D model for simulation of rock fracture and friction properties and induced seismicity in hydraulic stimulation of geothermal reservoir (Yoon et al. 2012b).

3. Model parameters and modelling plan

All the required model parameters will be collected from the SKB Data Report on Forsmark site (SKB, 2010), which includes mechanical and thermal properties of bedrock, discrete fracture network, model layout, etc. As this numerical study focuses on thermo-mechanical induced seismicity, the “initial temperate period” is chosen among the four time periods/climate domains. Table 1 lists variations that are to be taken into account in the numerical modelling. In total, 10 simulations are proposed out of all combinations, which are listed in Table 2 (refer to Table 1 for abbreviations).

Table 1. Modelling approach and abbreviations.

Modelling parameters	**Variations**
Model geometry	Near-field scale (NFS) Far-field scale (FFS) Single (SDH), double (DDH), multiple (MDH) deposition holes Layout D2 in rock domain RFM029
Length scale of DFN	Type 1: meter – decameter Type 2: hecto – kilometre
In-situ stresses	Most-likely stress model (MLSM) Maximum stress model (MXSM)
Simulated heating	Heat1: simultaneous heating Heat2: sequential heating
Fault	Singö Fault

Table 2. Simulation number and modelling conditions.

Model number	**Combination of the modelling conditions**	**Remarks**
1	NFS-SDH + DFN(Typ.1) + MLSM + Heat1	Side view (Fig.1, M1)
2	NFS-DDH + DFN(Typ.1) + MLSM + Heat1	Side view (Fig.1, M2)
3	NFS-MDH + DFN(Typ.1) + MLSM + Heat1	Side view (Fig.1, M3)
4	NFS-MDH + DFN(Typ.1) + MXSM + Heat1	Side view (Fig.1, M3)
5	FFS + DFN(Typ.2) + MLSM + Heat1 + Fault	Side view (Fig.1, M4)
6	FFS + DFN(Typ.2) + MLSM + Heat1	Plane view (Fig.2, M5)
7	FFS + DFN(Typ.2) + MXSM + Heat1	Plane view (Fig.2, M5)
8	FFS + DFN(Typ.2) + MLSM + Heat2	Plane view (Fig.2, M5)
9	FFS + DFN(Typ.2) + MXSM + Heat2	Plane view (Fig.2, M5)
10	FFS + DFN(Typ.2) + MLSM + Heat2 + Fault	Plane view (Fig.2, M5)

Figure 1 shows a schematic of the simulation model in near-field scale. For far-field scale (Fig. 2), the model dimension can span up to 4 km by 4 km. Unlike the near-field scale models where the geometry of deposition hole is treated in a more realistic way, the far-field models will treat deposition holes with waste canisters as point heat sources. Length scale of DFN in near-field and far-field models will differ, i.e. meter to decameter scale and hecto to kilometer scale, respectively. Two in-situ stress models will be tested (Most-likely and Maximum stress models). For some of the far-field models, the start of point source heating will vary simultaneous and sequential with interval of tens of years.
Results will be reported with stress, displacement and magnitudes of induced seismicity for specific points in the models and along cross sections for individual models. The onset of seismicity and magnitude variations as a function of modelling scale will be reported.

This modelling work will be conducted by Seoul National University SNU (South Korea), Steph Rock Consulting and the German Research Centre for Geosciences at Potsdam, Section 2.6 Seismic Hazard and Stress Field (Germany).

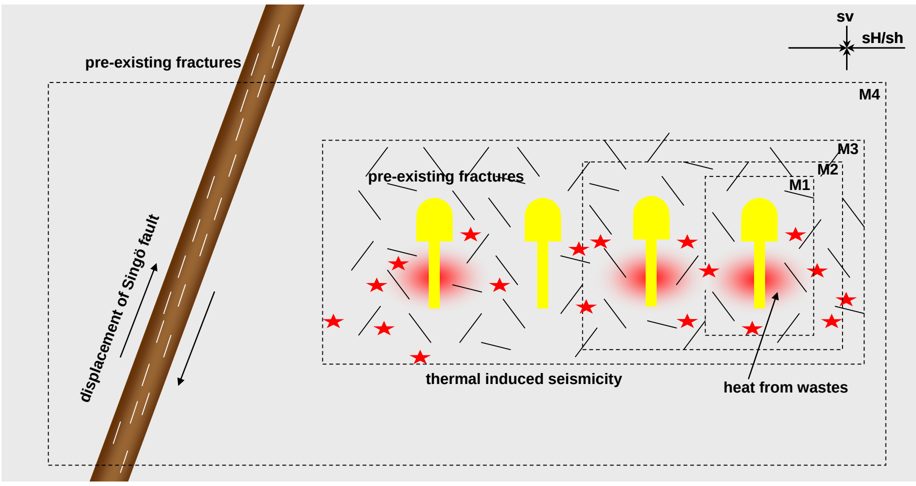

Figure 1. Schematic of near-field scale models (M1, M2 and M3) and far-field scale (M4). Note the acronyms M1, M2, M3 and M4 at the upper right corners of the boxed areas. Not to scale.

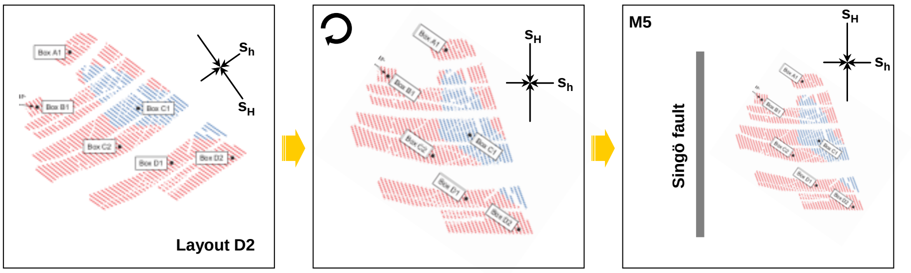

Figure 2. Schematic of far-field scale model. M5 is made by rotating SKB Layout D2 so that S_h and S_H are in horizontal and vertical direction for the sake of simplicity in modelling. Each deposition hole with canister will be converted to point heat sources.

4. References

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Topic 3.

THM coupling and fracture network evolution investigated by fracture mechanics approach

1. Background and motivation for independent study

The THM modelling for SR-Site by SKB has been mainly conducted by one and the same modelling technique -distinct element modelling –and the Itasca codes UDEC and 3DEC. In the review of the top documents of SR-Site it has been pointed out that there is a need for alternative modelling of the THM processes and the fracture network evolution due to the THM processes. Also, it has been pointed out that SKB has ignored fracture propagation from existing fracture networks and the THM processes. An alternative modelling with a fracture mechanics approach can provide a new insight about the long-term stability of the repository at the Forsmark site.

During Project 90 and Site-94 conducted by Swedish Nuclear Power Inspectorate (SKI), the 2-D fracture mechanics code FRACOD was firstly developed by Shen and Stephansson at Royal Institute of Technology (KTH) in Stockholm (SKI, 1996; Shen and Stephansson, 1996). The code was applied to the studies of long-term stability of the near-field of the KBS-3 concept for a repository of spent nuclear fuel. Ever since the developments supported by SKI (now SSM), the code has been further developed and applied to a large number of different rock engineering projects of which many are related to disposal of spent nuclear fuel and radioactive waste (Shen et al., 2012). Currently, the code is capable to study coupled TM and HM processes in two dimensions. These days further development starts with the aim of handling fully coupled THM behaviour of fractured rock masses and the development of a 3-D version of the FRACOD code. A research version of the 3-D code is available but it needs additional work about the graphic output to be fully applicable to Rock Engineering problems.

The aim of this study is to start the application of the fully coupled THM fracture mechanics code in 2-D to the problems related to a repository at the Forsmark site. In addition, the 3-D version of FRACOD will be partially applied to some of the key problems related to THM coupling and fracture network evolution.

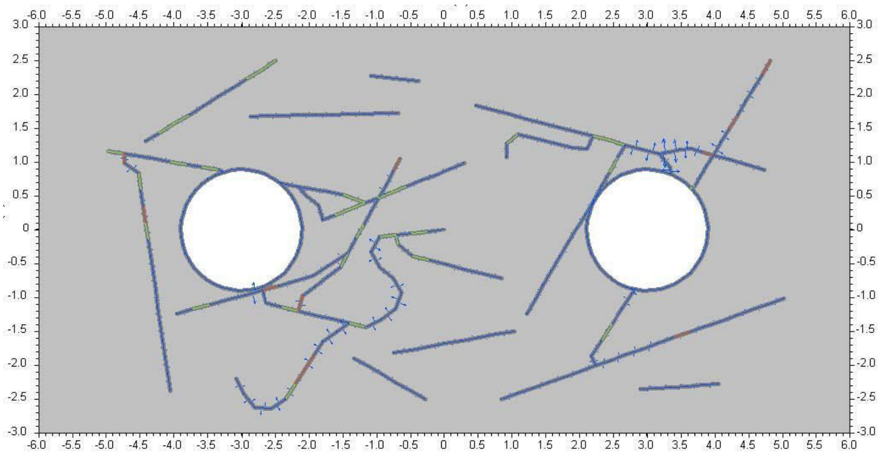

Figure 1. Example of fracture network evolution during glacial period (Backers and Stephansson, 2011).

2. Scope of the work

Each of the evolutionary phases in the development of the repository will be simulated, starting with the excavation followed by the thermal phase, water uptake and swelling pressure and related influence on the fracture initiation and propagation and groundwater flow. Of particular interest is the pressure increase from freezing of the bentonite during the permafrost stage and the excess groundwater flow during post-glacial phase. The FRACOD modelling conducted by Backers and Stephansson (2011) has demonstrated the importance of the estimated stress field to the rock mass response. Until SKB has determined the final in-situ stress field model at Forsmark, there is a need of conducting the studies for different assumptions about the stress field.

This study intends to tackle the technical issues related to fracture initiation and propagation in the repository in sufficient detail. The followings are the list of task that will be performed for the independent study:

1. Task 1. Discrete Fracture Network (DFN) evolution during excavation and temperate period
    a. DFN evolution due to excavation under various stress model – 2D fracture mechanics modelling
    b. DFN evolution due to excavation and temperature change –2D Coupled TM fracture mechanics modelling

2. Task 2. Discrete Fracture Network (DFN) evolution during permafrost and glacial period
    a. DFN evolution due to ice load – 2D Coupled HM fracture mechanics modelling
    b. DFN evolution due to swelling pressure – 2D Coupled HM fracture mechanics modelling with cyclic loading.

3. Task 3. Three-dimensional fracture mechanics modelling
    a. Fracture initiation and propagation due to excavation – 3D fracture mechanics modelling

b. Fracture initiation and propagation due to excavation and temperature increase – 3D coupled TM fracture mechanics modelling
c. Generation of sheet fractures (exfoliation) from de-stressing caused by erosion of sedimentary cover and melting of an ice sheet over Forsmark area.

This modelling work will be conducted by Seoul National University SNU (South Korea), Steph Rock Consulting and the German Research Centre for Geosciences at Potsdam (Germany). SNU and Steph Rock Consulting are members of the Consortium performing the code development of the fully THM coupling of FRACOD 2-D and the 3-D FRACOD.

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