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# Preliminary safety evaluation for the Laxemar subarea

## Based on data and site descriptions after the initial site investigation stage

Svensk Kärnbränslehantering AB

March 2006

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# Preface

This report presents the preliminary safety evaluation (PSE) of the Laxemar subarea, based on data from SKB's Initial Site Investigation stage. The report contains many references to specific sections of the Laxemar Site Descriptive Model report /SKB 2006a/. In order to enhance the reading of this PSE, it is preferable that the reader has access to that report to provide extended background and context.

Johan Andersson, JA Streamflow AB has authored this report.

Comments have been provided by Jan-Olof Selroos, Ignasi Puigdomenech and Raymond Munier of SKB's safety assessment team on issues regarding hydrogeology/radionuclide transport, hydrogeochemistry and geology, respectively. The undersigned has provided the thermal calculations and the calculation of the deposition hole exploitation ratio and associated text, as well as overall comments on the report.

The following members of SKB's site investigation project have also provided comments: Olle Olsson SKB, Peter Wikberg SKB, Karl-Erik Almén SKB and Anders Winberg Conterra AB. Comments has also be given by Christer Svemar SKB and Göran Bäckblom Conrox AB.

The report has been reviewed by the following members of SKB's international Site Investigation Expert Review Group (SIERG): Per-Eric Ahlström, Ivars Neretnieks, Mike Thorne, Lars Söderberg, Jordi Bruno, John A Hudson and Roland Pusch.

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Project Leader

# Summary

The main objectives of this Preliminary Safety Evaluation (PSE) of the Laxemar subarea have been to determine, with limited efforts, whether the feasibility study's judgement of the suitability of the candidate area with respect to long-term safety holds up in the light of the actual site investigation data; to provide feedback to continued site investigations and site-specific repository design and to identify site-specific scenarios and geoscientific issues for further analyses.

The PSE focuses on comparing the attained knowledge of the sites with the suitability criteria as set out by SKB in /Andersson et al. 2000/. These criteria both concern properties of the site judged to be necessary for safety and engineering (requirements) and properties judged to be beneficial (preferences). The findings are then evaluated in order to provide feedback to continued investigations and design work. The PSE does not aim at comparing sites and does not assess compliance with safety and radiation protection criteria. The latter is eventually done in coming Safety Assessments. Two reports on long-term safety, SR-Can and SR-Site, will be produced in 2006 and 2008, respectively. SR-Site will support the application to build a final repository. SR-Can is a preliminary version of SR-Site and will provide feedback to continued site investigations. It will also allow the Swedish authorities to comment on SKB's methodology for safety assessments before it is used in support of a licence application. SR-Can will be based on site data from the initial site investigation phase and SR-Site on data from the complete site investigations.

This preliminary safety evaluation shows that, according to existing data, the Laxemar subarea *meets all safety requirements*. The evaluation also shows that the Laxemar subarea meets most of the safety preferences, but for some aspects of the site description further reduction of the uncertainties would enhance the safety case. Despite the stated concerns, there is no reason, from a safety point of view, not to continue the Site Investigations at the Laxemar subarea. There are uncertainties to resolve and the safety would eventually need to be verified through a proper safety assessment.

Only some of the uncertainties noted in the Site Descriptive Model have safety implications and need further resolution for this reason. Furthermore, uncertainties may need resolving for other reasons, such as giving an adequate assurance of site understanding or assisting in optimising design. Notably, there are questions about the representativity of the rock mechanics, thermal, hydrogeological and hydrogeochemical samples. There are generally few data at depth from the rock domains where the potential repository might be located. The following feedback is provided to the site investigations and the associated site modelling:

- Reducing the uncertainty on the deformation zone geometry and character within the subarea will be needed to firmly ensure the location of suitable deposition volumes. The current uncertainty in the character and geometry of the deformation zones in the area means that the layout produced using the results of the initial site investigation (layout step D1) would likely need to be substantially altered when a less uncertain description is available.
- There is substantial and, as yet, not quantified uncertainty in the Discrete Fracture Network (DFN) model. Efforts need to be spent on quantifying and reducing these uncertainties. More data are needed from the potential repository volume, but there is also a limit on the degree to which these uncertainties can be reduced using only

information from surface-based investigations. Further reduction of the uncertainties in the size distribution, if needed, would probably only be possible from detailed investigations underground.

- Efforts need also be spent on improving the DFN-modelling. There are assumptions made in current models that could be challenged and there seems to be room for making better use of the borehole information. It is especially important to provide robust estimates of the intensity and size distribution of large fractures and deformation zones (expressed as $P_{32}$ and the $k_r$ parameter in the currently assumed power-law distribution) and further efforts should be spent on providing good support for the possible ranges of these parameters. In contrast, details of the orientation distribution of fractures are of much less importance.
- Considering the uncertain and relatively high stress levels in Stress Domain I (in the south western part of Laxemar), in combination with the comparatively low Uniaxial Compressive Strength (UCS) of the intact rock, further reductions in the uncertainties in stress and rock mechanics properties are needed. There is a need to obtain representative data from all important rock types in the potential repository volume. Also, the issue of spalling due to the thermal load from the deposited spent fuel would require additional analyses, as already envisaged for SR-Can. This may also lead to additional data demands.
- The recently relaxed thermal requirement puts a limit on the maximum temperature in the buffer to 100°C, but with no requirement on the canister temperature. The current repository layout, with a mean canister spacing of 7.4 m, has a considerable margin to the 100°C criterion for the peak buffer temperature. In fact, even a canister spacing of 6 m would possibly be sufficient to meet the thermal requirement on the buffer. However, in order to justify reducing the canister separation distance, making the layout more efficient, further reduction of uncertainties in the spatial variability and scaling of thermal conductivity would be necessary. More representative data from the potential repository volume are needed.
- More data from the rock mass of the potential repository volume are needed before it is meaningful to more elaborately try to bound the uncertainties and spatial variability of the rock mass hydraulic properties of the Laxemar subarea. There is a high variability of transmissivity within boreholes and the significance of the currently suggested depth dependence could be questioned. There is also a high variability in transmissivity between the relatively few boreholes, implying uncertainty when extrapolating the statistics of a single borehole to a larger area, i.e. the validity of attributing different hydraulic properties to different rock domains is not fully established. The importance of anisotropy, i.e. that fracture transmissivity may depend on fracture orientation, may also have been underestimated.
- Comparing the hydrogeochemical and hydrogeological descriptions suggest agreement in the conceptual understanding, but there are still several quantitative uncertainties in both descriptions. Representative data from repository depth at the Laxemar subarea are needed. There is also a lack of data on water composition in the low conductive fractures and in the matrix. This means that even though the hydrogeochemical requirements and preferences are met, further reduction of uncertainties in the spatial distribution at depth is desirable to further improve the understanding of the hydrogeochemistry and enhance the safety case.
- In order to have a full evaluation of the redox buffering capacity of the geosphere, more data on mineralogy, Fe(II) and sulphide content of the rock and amount of fracture minerals in contact with the flowing water would be needed.

- The estimates of the transport resistance entail many uncertainties, and this will call for a careful analysis within SR-Can and in the completion of the site investigations. More boreholes and subsequent assessment of the data will be needed to determine better bounds on the transport resistance. The analysis made as part of the Site Descriptive Modelling is based on data that do not fully represent the potential repository volume of the Laxemar subarea, as noted above. There is a need to reduce this uncertainty in the site description. A reduction of other uncertainties in the hydrogeological DFN-model is also needed in order to narrow the bounds given by the first-order evaluation provided.
- Existing data on the migration properties of the rock does not suggest any strong spatial variation or strong correlation between rock type and migration properties. The uncertainties are more of a conceptual nature, as will be further assessed within SR-Can. Nevertheless, more in situ data on the migration properties of the rock would enhance the safety case. Better feedback on this issue will be available in relation to the full migration analysis made within SR-Can.

The assessments made for the PSE also have implications for design, some of which are of a generic character to be considered also for the other sites. The most important such feedbacks are the following:

- Compared with the actual safety requirement for long-term mechanical stability of deposition holes, the design rules for discarding canister positions due to potential intersections with large fractures or deformation zones seem to be too restrictive. For this reason, SKB has now started a project aiming at estimating the probability of identifying the deposition holes intersected by large fractures. This assessment will also produce more realistic estimates of the degree-of-utilisation.
- Considering the recently relaxed thermal requirement, the current canister separation distance implies a considerable margin to the 100°C criterion for the peak buffer temperature. In fact, even a canister spacing of 6 m would possibly be sufficient for meeting the thermal requirement on the buffer. However, in order to justify reducing the canister separation distance, making the layout more efficient, further reduction of uncertainties in the spatial variability and scaling of thermal conductivity would be necessary as already stated. Furthermore, the thermo-mechanical consequences of a smaller canister separation distance may also need attention.
- The relatively high and spatially varying hydraulic conductivity requires special attention to implications of high inflow rates in terms of loss of potential deposition holes and special grouting needs.

Finally, this PSE also highlights issues that would have to be considered if the Laxemar subarea were to be assessed in a full safety assessment. Important such issues are assessing the probability of identifying large fractures intersecting potential deposition holes, assessing the likelihood and consequences of thermal spalling of deposition holes and assessing the implications of the relatively high and variable hydraulic conductivity of the subarea.

# Utökad sammanfattning

Målen för denna preliminära säkerhetsbedömning av delområde Laxemar är att med begränsade insatser värdera om förstudiens bedömning om kandidatområdets lämplighet ur säkerhetssynpunkt kvarstår i ljuset av nu tillgängliga platsundersökningsdata, att ge återkoppling till de fortsatta platsundersökningarna och arbetet med förvarsutformningen samt att identifiera platsspecifika scenarier och geovetenskapliga frågeställningar som kan behöva belysas i det fortsatta arbetet. Denna preliminära säkerhetsbedömning baseras på data tillgängliga vid slutet (november 2004) av de inledande platsundersökningarna.

Säkerhetsbedömningen innebär främst att erhållen kunskap om platsen jämförs med de lämplighetsindikatorer som SKB tidigare har presenterat /Andersson et al. 2000/. Kriterierna avser dels platsegenskaper som bedömts nödvändiga för säkerhet och projektering (krav) och platsegenskaper som bedömts vara fördelaktiga (önskemål). Resultatet av jämförelsen värderas sedan för att ge återkoppling till de fortsatta platsundersökningarna och projekteringsarbetet. Säkerhetsbedömningen innefattar inte att jämföra platser och det görs ingen direkt värdering om ett förvar på platsen uppfyller ställda krav på säkerhet och strålskydd.

## Värdering av platsens lämplighet ur perspektivet långsiktig säkerhet

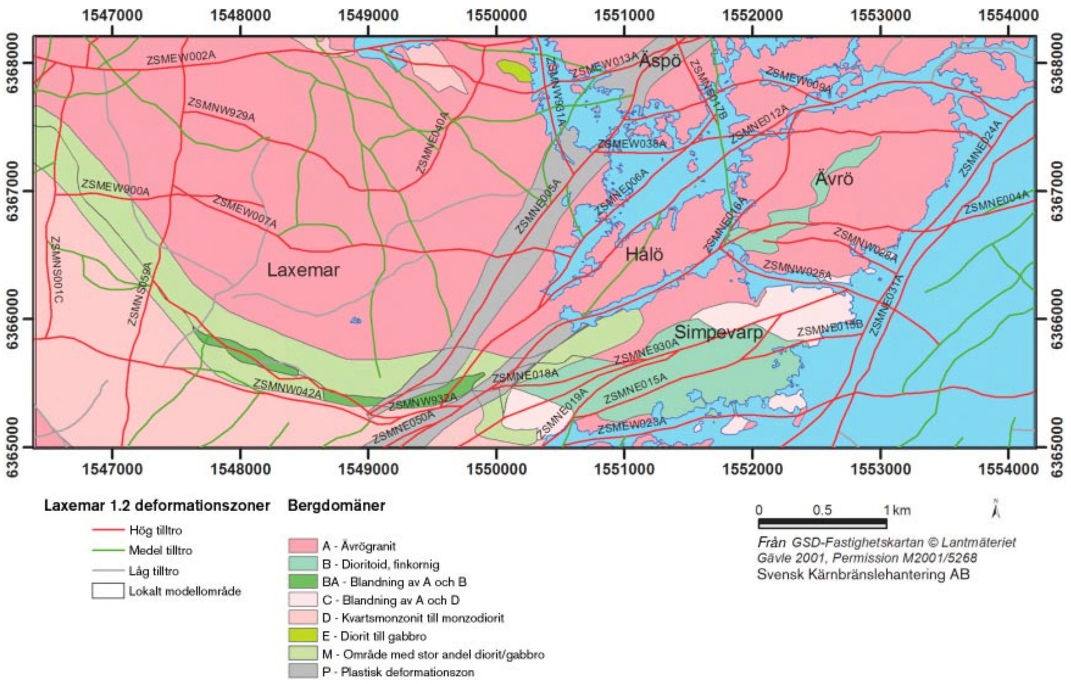
Utvärderingen visar, utifrån tillgängliga data, att delområde Laxemar *uppfyller alla ställda krav*. Följande slutsatser kan dras beträffande dessa krav:

- Noggranna undersökningar visar att delområde Laxemar inte har malmpotential. Bergartsfördelningen, figur 1, är typisk för granitisk berggrund och kvarvarande osäkerheter i bergartsfördelning har liten betydelse ur säkerhetssynpunkt.

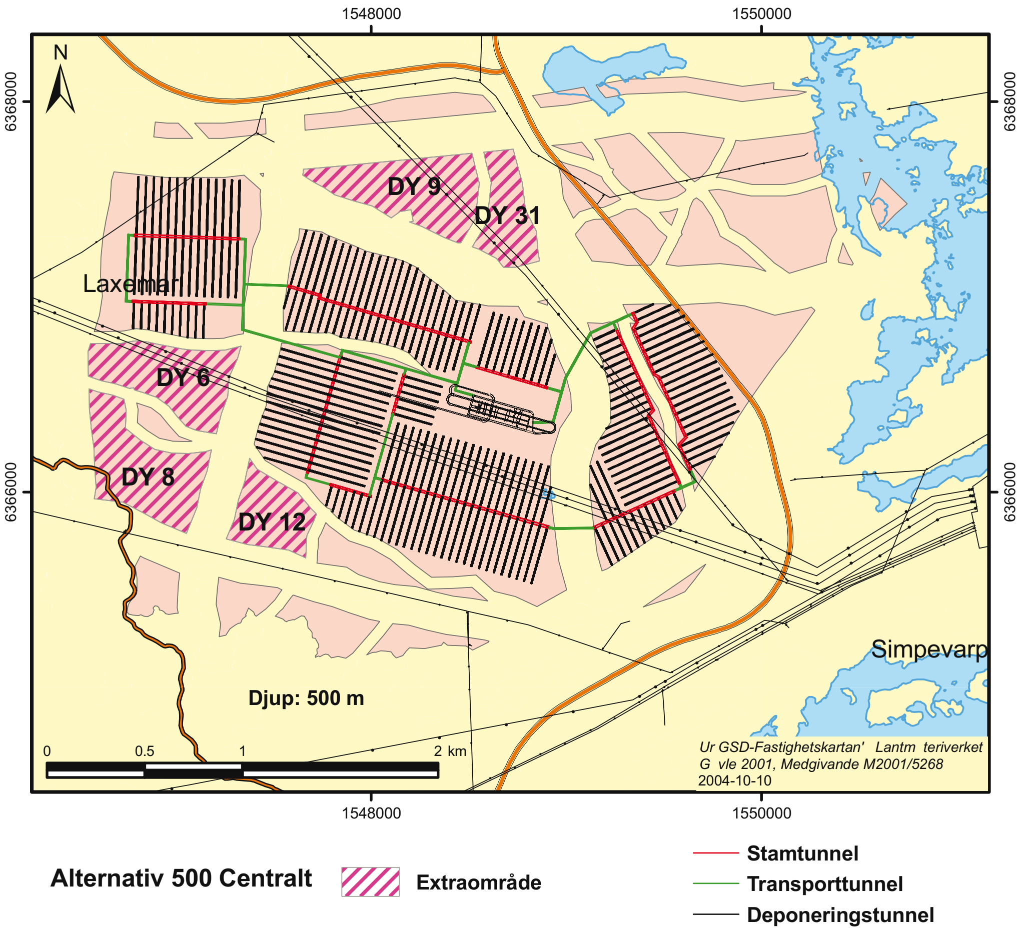
- En modell över bergets deformationszoner har tagits fram, figur 1, även om osäkerheter kvarstår i modellen. Det är klart möjligt att placera ett tillräckligt stort förvar med tillräckliga respektavstånd till deformationszoner inom delområdet, även om en låg nyttjandegrad antas, figur 2. Det finns även betydande reservområden. Kvarvarande osäkerheter om framförallt deformationzonernas karaktär och läge (geometri) mot djupet gör dock att den layout D1, som nu tagits fram, sannolikt kommer att behöva modifieras avsevärt när en mindre osäker modell av deformationszonerna tagits fram.

- Endast några få procent av alla tänkbara deponeringshål korsas av så stora sprickor eller mindre deformationszoner, dvs. sådana med en radie större än 75 m, att de inte kan användas för deponering. Andelen är dock osäker på grund av osäkerheter i modellen av bergets sprickor.

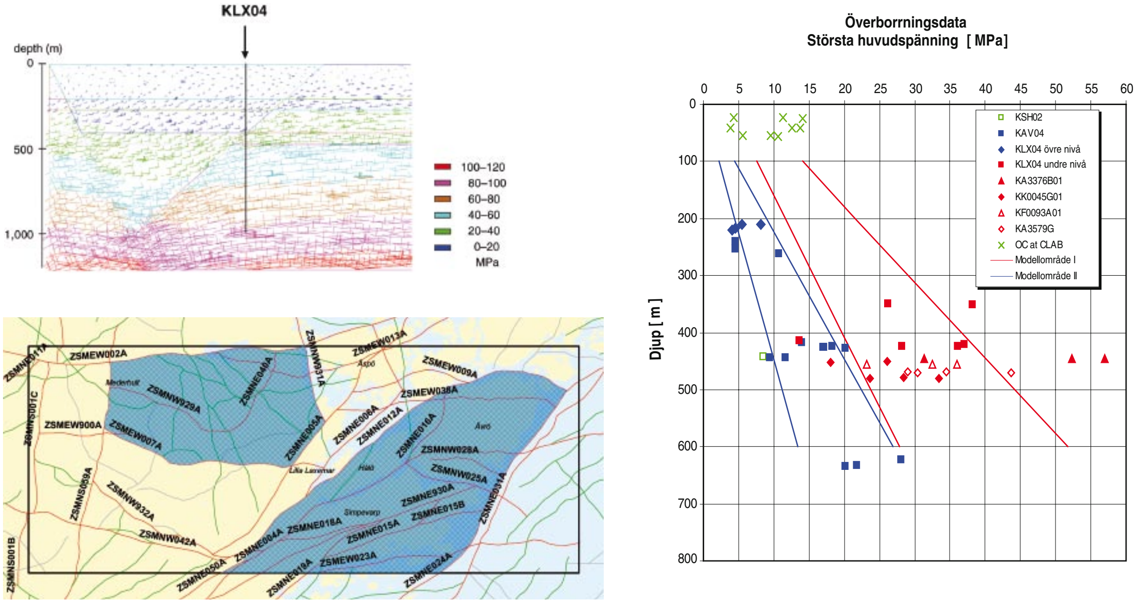
- Bergspänningarna är olika i olika bergvolymer, figur 3. I den s k spänningsdomän II är bergspänningarna låga och det finns ingen risk för smällberg eller andra spjälkningsfenomen oavsett förvarsdjup. Spänningsdomän II omfattar dock bara en begränsad del av den tänkbara förvarsvolymen. I spänningsdomän I är spänningarna högre, dock inte onormalt höga, medan det intakta bergets hållfasthet är något lägre än normalt, även om detta är osäkert. I spänningsdomän I görs därför bedömningen att det finns en ökande risk för spjälkning i deponeringshål vid förvarsdjup under 450 m. Den resulterande volymsförändringen bedöms dock vara mycket begränsad.



***Figur 1.*** *Geologisk beskrivning av Simpevarpsområde (där delområde Laxemar ingår). Figuren visar bergdomäner (bergartsfördelning) i ytan och modellerade deformationszoner med olika tilltro till existens: mycket troliga (röda), medeltroliga (gröna) och mindre troliga (grå). (Figur 11-4 i SDM L1.2).*



***Figur 2.*** *Tänkbar layout, med reservområden, anpassad till modellerade deformationszoner.*



*__Figur 3.__ Både data och numerisk modellering visar att delområde Laxemar kan delas in i två olika spänningsdomäner (I och II). Spänningsdomän II (visad med blå färg) har lägre spänningar, men förekommer inte i den sydvästra delen av området. (Figuren baseras på figurerna 6-5, 6-16 och 6-19 in SDM L1.2).*

- Även om bergets värmeledningsförmåga är relativt låg är det fullt möjligt att utforma ett förvar som uppfyller ställda temperaturkrav. Temperaturkraven har nyligen ändrats och ställer nu ett krav på en högsta temperatur om 100 °C i bufferten, men det finns inga temperaturkrav på kapseln. Den nu framtagna layouten, med ett medelkapselavstånd om 7.4 m, har därmed stor marginal till kriteriet om 100 °C i bufferten. Ett kapselavstånd ner till 6 m tycks i själva verket vara tillräckligt för att upprätthålla temperaturkravet i bufferten. Detta behöver dock underbyggas med ytterligare data om spridningen i bergets värmeledningsförmåga.

- Grundvattensammansättningen uppmätt på tänkbart förvarsdjup ligger tydligt inom krävda och önskade gränser. Enligt framtagna modeller kan grundvattnets sammansättning gränssättas av fyra olika referensvatten, men den exakta rumsliga fördelningen av grundvattensammansättningen är osäker. Dessutom saknas representativa vattenprover från den sydvästra delen av delområde Laxemar. Det finns dock ingen anledning att tro att sådana prover skulle uppvisa olämpliga förhållanden.

Utvärderingen visar också att delområde Laxemar uppfyller de flesta, ur säkerhetssynpunkt, ställda *önskemål*. I vissa fall skulle dock ytterligare reducering av osäkerheterna i platsbeskrivningen kunna ge mer robusta säkerhetsargument:

- Det finns en tänkbar risk för spjälkningsfenomen eftersom det intakta bergets hållfasthet är relativt låg i förhållande till de relativt sett höga spänningsnivåerna i spänningsdomän I. Det finns dock osäkerheter i bestämning av dessa parametrar. Dessutom saknas representativa data från viktiga bergarter inom den tänkbara förvarsvolymen.

- Beskrivningen av bergmassans vattengenomsläpplighet är osäker, speciellt beträffande den rumsliga fördelningen av bergets hydrauliska egenskaper. Modellresultat visar dessutom att vattengenomsläppligheten varierar kraftigt i rummet och att den ställvis är relativt hög. Enligt den hydrogeologiska modellen har cirka 75 procent av bergblock i 20 m skala i domän HRD(D,E,M) en vattengenomsläpplighet som är mindre än $10^{-8}$ m/s, medan bara drygt 50 procent av sådana bergblock i domän HRD(A) har en så låg vattengenomsläpplighet. Det är därför tveksamt om önskemålet om låg vattengenomsläpplighet kan anses vara uppfyllt. Osäkerheterna är också stora, framförallt på grund av att det bara finns få representativa data från det tänkbara förvarsområdet och den stora rumsliga variationen hos de data som finns.

- Modellresultat visar att bergets flödesberoende transportegenskaper, darcyflöde och transportmotstånd, i stort tycks uppfylla ställda önskemål. Gränssättande analyser resulterar i cirka 10 procent transportvägar med ett transportmotstånd som är lägre än $10^4$ år/m. Analyserna är dock osäkra. Andelen deponeringshål med lågt transportmotstånd motsvarar inte exakt motsvarande andel transportvägar eftersom ett deponeringshål kan vara förbundet med olika antal vägar (från noll till flera). För säkerhetsanalysen behöver därför en uppskalning göras, med olika antaganden om DFN modellens egenskaper. Kanalbildning inom enskilda sprickor kan, men behöver inte, ytterligare reducera transportmotståndet. Sådan uppskalning och vidare osäkerhetsanalys genomförs också inom ramen för den pågående säkerhetsanalysen SR-Can. Osäkerheterna är också stora på grund av att det bara finns få representativa data från det tänkbara förvarsområdet och den stora rumsliga variationen hos de data som finns.
- Bergmatrisens transportegenskaper (porositet, formationsfaktor och sorptionsegenskaper) uppfyller ställda önskemål, men resultaten bygger bara på ett fåtal provtagningar. Även mätta sorptionsegenskaper ligger inom de intervall som använts i tidigare säkerhetsanalyser, utom för Ra(II), om vattnet är salt, och för Am(III), som uppvisar lägre värden än vad som tidigare antagits. Osäkerheterna i mätningarna är dock stora, och dessa skillnader beror knappast på platsens egenskaper utan mer på metodmässiga osäkerheter. Inverkan på fördröjningen av radionuklider bedöms dessutom bli begränsad. Osäkerheterna hos sorptionsegenskaperna och betydelsen för radionuklidtransporten behöver noggrant belysas i SR-Can.

Sammanfattningsvis gäller dock att det från säkerhetssynpunkt inte finns någon anledning att inte fortsätta platsundersökningarna i delområde Laxemar. Det finns kvarvarande osäkerheter och om ett förvar skulle lokaliseras till området behöver säkerheten verifieras i en fullständig säkerhetsanalys som baseras på ett mer fullständigt dataunderlag.

## Återkoppling till de fortsatta platsundersökningarna

Det är bara en del av de osäkerheter som framgår av platsbeskrivningen som har betydelse för säkerheten och som ur denna aspekt skulle behöva reduceras. Generellt gäller att det efter de inledande platsundersökningarna inte finns tillräckligt mycket representativa data om bergets mekaniska, termiska, hydrogeologiska och hydrogeokemiska egenskaper inom den tänkta förvarsvolymen (se Figur 2). SKB avser att ta fram detta viktiga underlag under de fortsatta platsundersökningarna. Den preliminära säkerhetsbedömningen visar dessutom vilka ytterligare data som är viktiga att samla in, vilket beskrivs i det följande.

Osäkerheterna i geometrin for deformationszonerna inom delområdet behöver minska för att en mer precis förvarslayout ska kunna tas fram. Osäkerheterna i den nuvarande modellen är så stora att det är troligt att den nuvarande layouten D1 kommer att väsentligen behöva modifieras när en mindre osäker beskrivning av deformationszonerna blir tillgänglig. De fortsatta undersökningar som för detta syfte föreslås i platsmodellrapporten bedöms som lämpliga.

Osäkerheterna i den diskreta spricknätverksmodelleringen (DFN) är betydande och dessa påverkar centrala säkerhetsaspekter, som sannolikheten för att stora sprickor, eller mindre deformationszoner, korsar deponeringshål, uppskalning av hydrauliska egenskaper och resulterande transportmotstånd längs transportvägar från eventuellt skadade kapslar.

Insatser behövs för att minska dessa osäkerheter, både insamlande av ytterligare data och förbättrad platsmodellering. Det är speciellt viktigt att ta fram robusta skattningar av intensiteten av långa sprickor, dvs. den s k *k*-parametern och $P_{32}$ i den fördelningsfunktion som används i DFN-modelleringen. Det finns idag få observationer i det storleksintervall av sprickor som inte bör korsa deponeringshål, dvs. från hundra till några hundra meter. Det är därför angeläget att öka tilltron i just detta intervall i storleksfördelningen. De fortsatta undersökningar som för detta syfte föreslås i platsmodellrapporten bedöms som lämpliga. Det finns dock, sannolikt, en gräns för hur mycket ytbaserade undersökningar kan reducera osäkerheterna. Om ytterligare osäkerhetsreduktion behövs kan detta troligen endast göras medelst undersökningar under jord.

Det är också vikigt att förbättra själva DFN-modelleringen. Gjorda antaganden i nuvarande modeller kan kritiseras och informationen från borrhål och karteringar tycks kunna nyttjas bättre. Det gäller speciellt insatser för att få fram robusta gränser för sprickornas storleksfördelning. Jämfört med detta är beskrivningen av sprickornas orientering av mycket mindre betydelse.

De relativt sett höga spänningsnivåerna i spänningsdomän I, som bland annat utgör större delen av sydvästra delen av Laxemar, och det intakta bergets relativt låga hållfasthet påverkar riskbedömning för om det kan uppstå spjälkningsfenomen. För att ge bättre prognoser behöver osäkerheterna i bergspänningar och bergets mekaniska egenskaper reduceras ytterligare. Det behövs representativa data från alla viktiga bergarter inom den tänkbara förvarsvolymen. De fortsatta undersökningar som för detta syfte föreslås i platsmodellrapporten bedöms som lämpliga. Dessutom kan analysen av eventuell termisk spjälkning av berget i deponeringshål på grund av temperaturlasten, som genomförs inom den pågående säkerhetsanalysen SR-Can, komma att ställa ytterligare krav på data.

Ytterligare reduktion av osäkerheterna i den rumsliga variationen och uppskalningen av bergets värmeledningsförmåga skulle kunna tillåta en ännu mer effektiv layout. För att väsentligt kunna minska kapselavståndet behöver dock osäkerheten om värmeledningsförmågans rumsliga variation och uppskalning reduceras. Speciellt uppmärksamhet bör därvid fästas vid den tänkbara anisotropin och storleksfördelningen hos sekundära bergarter, med avvikande ledningsförmåga, inom den tänkbara förvarsvolymen i Laxemar. De fortsatta undersökningar och analyser som för detta syfte föreslås i platsmodellrapporten bedöms som lämpliga.

Det behövs väsentligt fler hydrogeologiska tester inom den tänkbara förvarsvolymen, innan det är möjligt att gränssätta osäkerheter och rumslig variation hos bergets vattengenomsläpplighet. Den begränsade datamängden, den oklara representativiteten kombinerat med den stora variabiliteten hos tillgängliga data gör att nu framtagna samband mellan djup och genomsläpplighet liksom samband mellan genomsläpplighet och olika bergdomäner, kan ifrågasättas. Betydelsen av bergmassans anisotropi kan också ha underskattats. De fortsatta undersökningar och analyser som för detta syfte föreslås i platsmodellrapporten verkar lämpliga, men kan dessutom behöva kompletteras med ytterligare borrhål.

De hydrogeologiska och hydrogeokemiska beskrivningarna redovisar en samstämd konceptuell bild, men det finns fortfarande betydande kvantitativa osäkerheter. Det behövs representativa kemiska data från förvarsdjup inom Laxemarområdet. Mer data om sammansättningen hos vattnet i bergmatrisen är också önskvärda. En reducering av osäkerheterna i den hydrogeokemiska modellen skulle öka förståelsen och därmed ge ytterligare säkerhetsargument. För att tillåta en mer fullständig analys av geosfärens redoxbuffringsförmåga behövs mer mineralogiska data såsom innehåll av Fe(II) och sulfid i bergmatrisen samt mängden sprickmineral i kontakt med det flödande vattnet. De fortsatta undersökningar och analyser som för dessa syften föreslås i platsmodellrapporten bedöms som lämpliga.

Uppskattningen av bergets transportmotstånd innehåller många osäkerheter. Framförallt skulle mer hydrauliska data från den tänkbara förvarsvolymen, med tillhörande analyser, möjliggöra en mer säker gränssättning av dessa egenskaper.

Bedömningen av bergmatrisens transportegenskaper (porositet, formationsfaktor och $K_d$) bygger bara på ett fåtal prov, men uppvisar å andra sidan ingen större rumslig variation. Osäkerheterna är mer av principiell art. Analys av fler prov skulle hursomhelst öka förståelsen. Bättre återkoppling i denna fråga kan bara göras i samband med de fullständiga radionuklidtransportsanalyser som genomförs inom ramen för SR-Can.

## Återkoppling till den fortsatta bergprojekteringen

Den preliminära säkerhetsbedömningen drar också några slutsatser av betydelse för det fortsatta arbetet med bergprojekteringen. En del av dessa slutsatser är allmänna och har därför betydelse även för de andra platserna som nu studeras.

Jämfört med de faktiska säkerhetskraven är projekteringens regler för att utesluta deponeringshål på grund av att de korsar för stora sprickor alltför restriktiv. SKB har därför påbörjat ett projekt som syftar till att bestämma sannolikheten att hitta de tänkbara deponeringshål som korsas av diskriminerande sprickor eller deformationszoner. Analysen bör också kunna ge en mer realistisk bedömning av nyttjandegraden.

Den nu framtagna layouten, med ett medelkapselavstånd om 7.4 m, har stor marginal till kriteriet om 100 °C i bufferten. Ett kapselavstånd ner till 6 m tycks i själva verket vara tillräckligt för att upprätthålla temperaturkravet i bufferten. För att väsentligt kunna minska kapselavståndet behöver dock, som redan konstaterats, osäkerheten om värmelednings-förmågans rumsliga variation och uppskalning reduceras. Inverkan av termospänningar kan dessutom behöva studeras ytterligare om kapselavstånden minskas.

Den relativt höga och starkt varierande vattengenomsläppligheten gör att speciell uppmärksamhet behöver fästas på frågor om vatteninläckage, bortfall av deponeringshål på grund av höga inflöden och resulterande injekteringsbehov för att kunna hantera dessa frågor.

## Återkoppling till kommande säkerhetsanalyser

Den preliminära säkerhetsbedömningen uppmärksammar slutligen ett antal frågeställningar som behöver beaktas om delområde Laxemar skulle analyseras i en fullständig säkerhetsanalys. En del av dessa frågeställningar är av generisk natur och bör därför även beaktas för andra platser. Andra är mer specifika för Laxemar.

Bedömningen av andelen kapslar som korsas av sprickor eller deformationszoner med radie över 75 m, som redovisas i denna rapport, tar inte hänsyn till möjligheten att hitta sådana deponeringshål och därmed undvika att deponera kapslar i dem. För säkerhetsanalysen behöver sannolikheten för denna möjlighet bedömas. Värderingar av praktiskt användbara metoder för att identifiera deponeringshål med diskriminerande sprickor behövs för att konsekvensen av post-glaciala förkastningar ska kunna bedömas. Preliminära sådana värderingar kommer att göras inom SR-Can.

Trots att bergets hållfasthet är relativt låg i relation till bergspänningarna, verkar smällbergsfenomen under bygge och drift vara hanterbara problem med liten inverkan på den långsiktiga säkerheten. Möjligheterna till och konsekvenserna av uppsprickning och spjälkning av berg i deponeringshål på grund av termolasten efter deponering behöver dock beaktas. Sådan spjälkning behöver inte utgöra något allvarligt problem för den långsiktiga säkerheten eftersom spjälkningen blir mycket lokal och sedan stabiliseras. Fenomenet och dess konsekvenser kommer dock att studeras inom SR-Can.

Den relativt höga och starkt varierande vattengenomsläppligheten och resulterande höga flöden in i deponeringshål före förslutning och omkring deponeringshål efter förslutning förtjänar speciell uppmärksamhet. Höga flöden kan påverka buffertens stabilitet och ger dessutom större utflöden av radionuklider om en kapsel skulle gå sönder.

De relativt enkla överslagsberäkningarna av bergets transportmotstånd visar att det går att sätta en undre gräns för transportmotståndet. SR-Can kommer att behöva studera dessa osäkerheter mer ingående och studera hur denna analys skalas till enskilda deponeringshål.

Fördröjningen för en radionuklid är elementspecifik och betydelsen av fördröjningen beror på hur den frigörs och radionuklidens halveringstid. Den platsspecifika informationen om bergmatrisens transportegenskaper behöver kompletteras med mer generella data tillsammans med en värdering av hur egenskaperna påverkas av olika konceptuella osäkerheter om transportprocesserna i bergmatrisen. Att kombinera platsspecifika och generella data och utvärdera osäkerheter relaterade till dessa utgör en viktig del av en säkerhetsanalys och kommer att göras inom SR-Can, men ligger utanför målsättningen med den preliminära säkerhetsbedömningen.

Det verkar som om utvecklingen av grundvattnets framtida sammansättning tillräckligt väl kan gränssättas inom ramen för de olika referensvatten som har identifierats i den modellerade volymen. I säkerhetsanalysen behövs dock en värdering om det finns någon process eller annan indikation som skulle kunna underminera ett sådant antagande.

Dessutom finns det ett antal platsspecifika frågor, som inte har med bergets egenskaper att göra, men som behöver studeras i en fullständig säkerhetsanalys. Ett exempel på en sådan fråga är inverkan av det relativt näraliggande Äspölaboratoriet.

# Contents

# 1 Introduction

This report is a Preliminary Safety Evaluation (PSE) of the Laxemar subarea being investigated by SKB as a candidate site for a final repository for spent nuclear fuel. Similar evaluations have been conducted for the Simpevarp subarea /SKB 2005a/ and for the Forsmark area /SKB 2005b/.

## 1.1 Purpose and objectives

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co., SKB. Systems are already in place for handling operational waste and for transporting and intermediate storing of the spent nuclear fuel. The two principal remaining tasks in the programme for the spent fuel are to locate, build and operate i) an encapsulation plant in which the spent fuel will be emplaced in canisters and ii) a final repository where the canisters will be deposited.

For this reason, SKB is pursuing site investigations for the final repository in the municipalities of Östhammar, the Forsmark area, and Oskarshamn. In Oskarshamn, the area is divided into two parts, the Simpevarp subarea, concentrated on the Simpevarp Peninsula and the Laxemar subarea located on the mainland west of the Simpevarp Peninsula, see Figure 1-1.

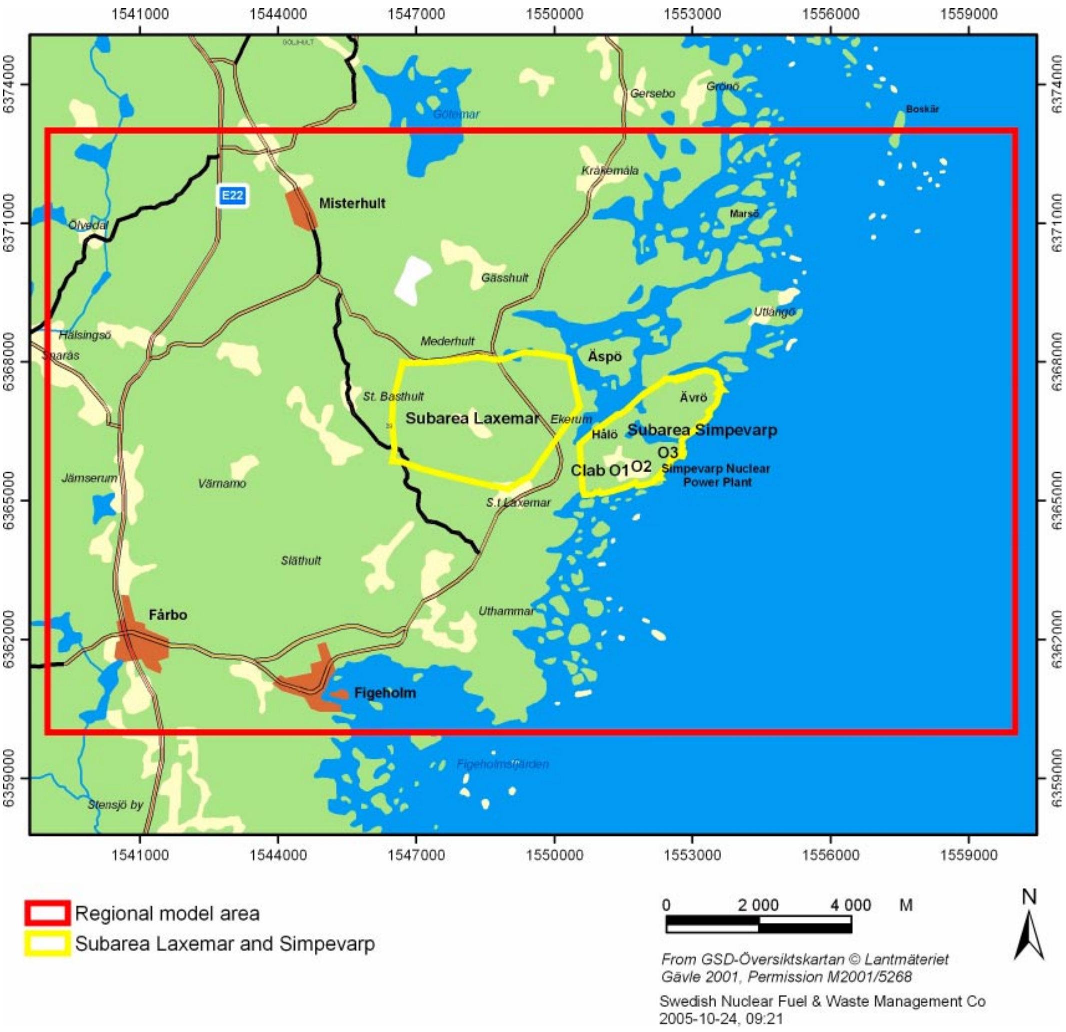
The investigations /SKB 2001/ are carried out in two stages, an initial investigation followed by a complete investigation, should the results after the initial stage be favourable. The initial stage has been completed for the Laxemar subarea and reported in the preliminary Site Descriptive Model version 1.2 of the Laxemar subarea /SKB 2006a/.

A PSE is made at the end of the initial stage, based on available field data and preliminary layouts for the final repository. Similar evaluations have been conducted for the Simpevarp subarea /SKB 2005a/ and for the Forsmark area /SKB 2005b/.

The main objectives of the evaluation are:

- to determine whether the feasibility study's judgement on the suitability of the candidate area with respect to long-term safety holds up in the light of the findings from the site investigation,
- to provide feedback to continued site investigations and site-specific repository design and
- to identify site-specific scenarios and geoscientific issues for further analyses.

The PSE is concerned with site suitability with respect to radiological long-term safety, but does not formally assess compliance with safety and radiation protection criteria. Furthermore, it does not aim to compare sites. Environmental effects due to the construction and operation of the repository will be addressed in the environmental impact assessment and are not discussed here.



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Swedish Nuclear Fuel & Waste Management Co
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***Figure 1-1.*** *Overview of the Simpevarp area and identification of the Simpevarp and Laxemar subareas (Figure 1-2 of SDM L1.2).*

## 1.2 Overview of methodology

In order to meet the objectives, the PSE focuses on comparing the attained knowledge of the sites to the suitability criteria as set out by SKB in /Andersson et al. 2000/. Some of these criteria are absolute requirements whereas others are preferable conditions that would influence safety in a positive manner. The criteria are formulated for the different subject areas of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry and radionuclide transport.

The assessment, presented in Chapter 3, follows these subject areas. First, the criteria are presented, but consideration is also given to whether these criteria need to be modified due to findings or design changes made since the issuing of the criteria. After presenting the criteria and the additional considerations, the relevant findings from the Site Modelling /SKB 2006a/ and the design work /SKB 2006b/ are presented. Usually these analyses are sufficient to address the performance relative to the criteria, but in some instances some additional calculations, performed directly by the Safety Assessment team, are added. After presenting these results, there is an evaluation of the degree to which the criteria and additional considerations are fulfilled with respect to safety and what feedback may be given to the further site investigation and repository design work.

## 1.3 Developments since the planning document and implications for the PSE

Since the issue of the PSE planning document, SKB's Safety Assessment planning has evolved and relationships between activities related to site investigations and safety assessments have been further detailed. Two reports on long-term safety, SR-Can and SR-Site, will be produced in 2006 and 2008, respectively. SR-Site will support the application to build a final repository. SR-Can is a preliminary version of SR-Site and will provide feedback to continued site investigations. It will also allow the Swedish authorities to comment on SKB's methodology for safety assessments before it is used in support of a licence application. SR-Can will be based on site data from the initial site investigation phase and SR-Site on data from the complete site investigations. An interim version of SR-Can /SKB 2004a/ has already been published.

According to the current basis for planning, the complete site investigations will concern the Forsmark and Laxemar areas and both SR-Can and SR-Site will consequently consider potential repositories located in these two areas. The main reasons, currently envisaged, for setting aside the Simpevarp subarea at this stage are flexibility and space considerations. Available underground space for a final repository is expected to be limited at the Simpevarp subarea in comparison with the two other candidate areas. The definite decision on what subarea, Laxemar or Simpevarp, to prioritize in Oskarshamn will consider the findings of this preliminary safety evaluation of the data from the Laxemar subarea.

An objective of SR-Can is to give a preliminarily assessment of the safety of the Forsmark and Laxemar sites given the descriptions of the canisters to be produced in the encapsulation plant and the host rock conditions at the sites, in so far as they can be specified after the preliminary site investigation phase. The intention is not to fully establish the suitability of the studied sites – this will be done in SR-Site. The intention is also not to finally establish the technical system for disposal – but rather to investigate the safety of the system as it is specified at this stage, and to give feedback for further developments. However, it is important already at the time of SR-Can to have established the likely viability of disposal at one or both of the sites.

Preliminary Safety Evaluations are being made for all sites, i.e. including the Simpevarp subarea. The evaluations are undertaken as sub-tasks within the SR-Can project. However, some of the analyses envisaged in the PSE planning document /SKB 2002a/ will now appear as either sub-tasks in SR-Can or as part of Site Descriptive Modelling or Repository Engineering activities, see further Section 3.1. The implications of this are discussed in Section 3.8, but it can generally be stated that the combination of the current level of PSE with the more detailed evaluation in SR-Can implies a more thorough evaluation of findings of the initial site investigations than originally envisaged.

## 1.4 INSITE review of the PSE for the Simpevarp subarea

The PSE planning document /SKB 2002a/ has been reviewed by the SKI international review group INSITE /SKI 2004/. SKB comments to this are found in the previous PSE reports published. Furthermore, the INSITE group has also reviewed /SKI 2005/ the PSE of the Simpevarp subarea /SKB 2005a/. Apart from generally concluding that the report meets its objectives, the following main points were brought up in the review:

- *The layout of the repository has included areas located "outside" the subarea, to the north, west and south, respectively. There is a lack of data for these areas and this indicates that the original Simpevarp subarea is too small to host a single layer repository.*

- *The dispersed character of the repository indicates a lack of information about rock type distribution at repository depth… The possible existence of unexpected structures that could affect the layout must be considered high.*
- *The definition of respect distance as "…the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to potential future seismic effects on canister integrity" deviates strongly from the definition used in previous SKB studies, such as KBS-3. An important part of the respect distance was to ensure significant retardation of escaping radionuclides from the repository.*
- *One aspect of the new approach is to be able to identify "discriminating fractures" of radius larger than 50 m. It may be questionable to try to apply this type of discriminating factor (size of intersecting fracture) when identifying which canister deposition-boreholes should be rejected. The character of the structures may be a better basis for identification of discrimination structures (fractures or fracture zones).*
- *Ground water transport in the bedrock takes place mainly along fracture and fracture zones and the report points out that there are "substantial uncertainties with respect to the channelling of individual fractures". It is not apparent what type of channelling is meant.*
- *The labelling of rock types in rock domains is not uniform. The rock nomenclature used by SKB has no uniform base (being a mix of texture and mineralogy) and this implies, especially for the Ävrö granite, that the thermal conductivity may vary strongly.*
- *SKB writes that "The ore potential is considered negligible, with a real potential only for quarrying of building- and ornamental stone associated with the Götemar and Uthammar granite intrusions to the north and south of the investigated area, respectively." This review agrees with this statement. It should be noted that the Götemar and Uthammar granites are located outside the Simpevarp subarea but occur inside the Simpevarp area (i.e. the regional model area).*
- *Not all of the data related to the initial site investigation (ISI) are used. How will data from borehole KAV04 affect the potential available volume for a repository?*
- *INSITE would like to see additional stress measurements added to the list of remaining issues specific to the Simpevarp subarea presented at the end of Section 2.1 of the PSE report.*
- *… the NW deposition units F – I are located in the relatively `high stress region´ east of deformation zone ZSMNE012A. There might also be a potential lack of information about additional deformation zones in the water covered area northeast of this deformation zone.*
- *INSITE disagrees with SKB's statement that thermally induced enhanced spalling is unlikely at the Simpevarp subarea due to the low stress levels.*
- *INSITE finds that … the calculations of the thermal influence of gaps between the canister and buffer and between buffer and rock, and also the uncertainties/variability in rock thermal conductivity should be revisited.*

These concerns will be addressed in this PSE, to the extent they are also applicable to the PSE and the Laxemar subarea. In particular:

- The definition of respect distance has been revised since the original thoughts were presented in previous studies. Radionuclide migration is indeed still an important issue, but the application of respect distances is not an appropriate means of constraining this. As further discussed in Section 3.7.3, retention is primarily controlled by the properties (transmissivity distribution of the flowing fractures) of the rock mass, which means that it is not meaningful to define a generic respect distance. Instead, the safety assessment explores the resulting transport resistance from each potential deposition hole position.

- SKB is exploring various means of identifying potentially “discriminating fractures” using various types of indicators, including assessing the character of the structures, in a special project (Expect). The overall findings will also be reported in SR-Can.
- The different aspects of channelling are partly discussed in SDM L1.2 and this discussion is also reflected in this PSE. Further discussion and evaluation of the importance of channelling will be provided in SR-Can.
- Uncertainty concerning the stress regime indeed motivate additional stress measurements at the Laxemar subarea, as is further discussed in this PSE. The need for assessing thermally induced spalling is noted in this PSE. The issue will be assessed in SR-Can.

In further response to these views, it should be noted that the PSE is not the sole form of feedback to the Site Investigation activities. Several individuals from the SR-Can team are e.g. deeply involved in the site modelling from which much feedback to the Site Investigations is given. Furthermore, a formal check of the Complete Site Investigation (CSI) programme will be made after each completed PSE which will allow for adding complementary investigation activities for the later data freezes of the CSI, if such investigations activities are judged to be needed.

It need also be noted that the comments provided by INSITE, as well as by the SKB internal reviewers, have led to a successive development of the PSE:s for the three sites. Hence, they are slightly different and not directly comparable and should not be used to compare sites as already stated in Section 1.1.

# 2 Basis for the safety evaluation

This chapter provides a brief overview of the Site Descriptive Model of the Laxemar subarea and of the engineering work that has been undertaken in order develop a preliminary repository design. This input is used in the evaluation presented in Chapter 3.

## 2.1 Site Descriptive Model

The preliminary site description of the Laxemar subarea version 1.2, /SKB 2006a/ and denoted SDM L1.2 in this document, is based on the field data collected during the initial site investigation phase. Also, the findings from the earlier versions of the site description relating to the Simpevarp and Laxemar subareas, namely SDM S1.2 /SKB 2005c/, SDM S1.1 /SKB 2004b/ and version 0 /SKB 2002b/, are incorporated in SDM L1.2. The site descriptive model is presented on a local and a regional scale, see Figure 2-1, with an accompanying synthesis of the current understanding of the site.

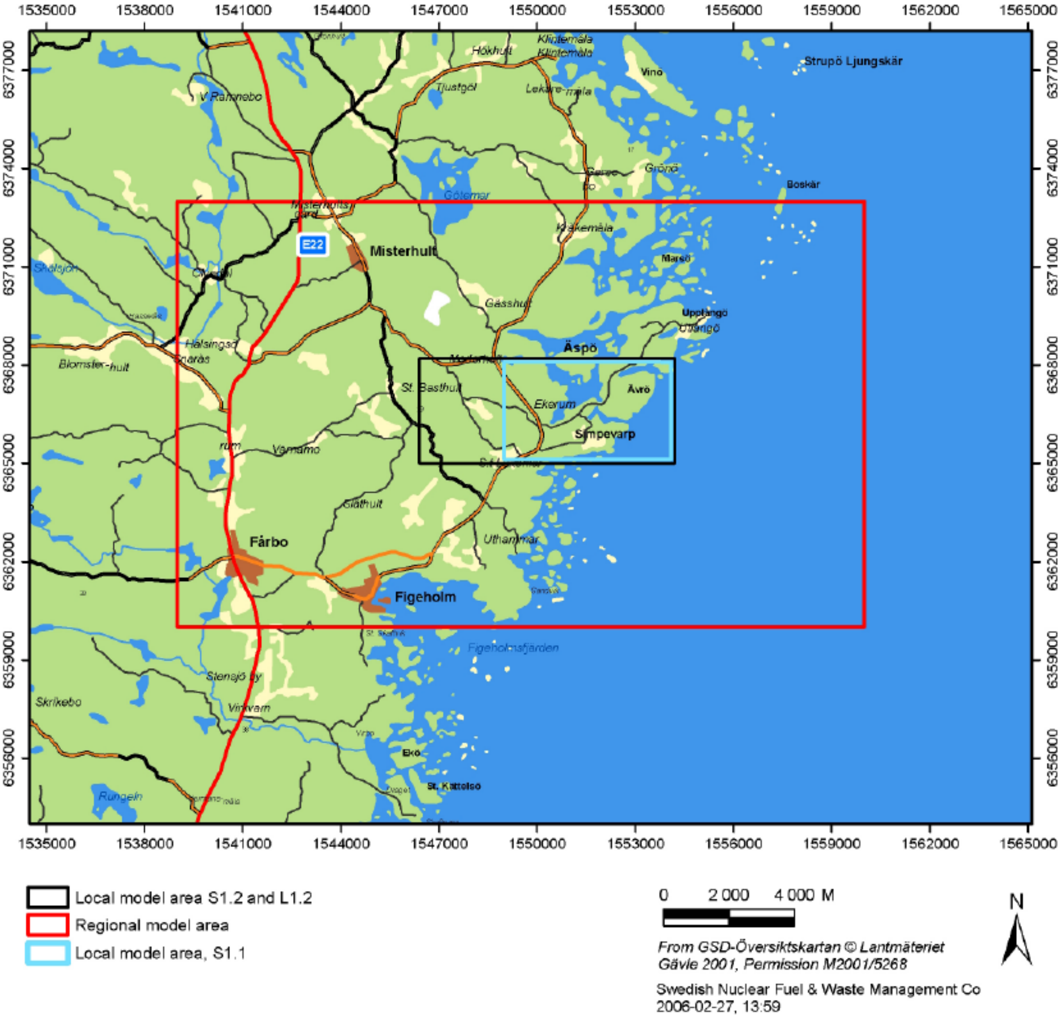

*Figure 2-1. Regional and local model areas used for Laxemar 1.2. The areal coverage of the regional model is the same as that used in Simpevarp 1.2 /SKB 2006a, Figure 2-4/.*

### 2.1.1 Investigations and available data

Investigations have been in progress at the Simpevarp area from about March 2002. The data freeze for the Simpevarp 1.1 model version was set at July 1, 2003 and reported in the version S1.1 Site Descriptive Model Report /SKB 2004b/. The data freeze for version Simpevarp 1.2 was set at April 1, 2004 and reported in version S1.2 Site Descriptive Model Report /SKB 2005c/. The data included in data freeze Laxemar 1.2 and available for the Laxemar 1.2 modelling work are the data used in previous model versions, as described above, and data acquired between data freezes S1.2 and L1.2 (i.e. during the period April 1, 2004 and November 1, 2004). The database also consider the data assembled before the start of site investigations.

The surface investigations (including marine and lacustrine investigations) undertaken in the Simpevarp regional area and its surroundings carried out between data freezes S1.2 and L1.2 comprised the following.

- Bedrock mapping (lithology, structural characteristics, geochronology).
- Investigations of Quaternary deposits including indirect assessments of marine and lacustrine sediments in the Baltic and in Lake Frisksjön. The investigations have included stratigraphy, element distribution in the till, sediment samples and peatland investigations.
- Surface geophysical investigations, including acquisition of new data and updated/expanded interpretations of data collected before data freeze S1.2 (primarily reflection seismic data).
- Meteorological and hydrological measurements and monitoring (precipitation, snow depth, ground frost, ice cover, surface water levels, run-off in streams and brooks).
- Hydrogeochemical sampling and analysis of precipitation, surface waters and shallow groundwater.
- Various ecological inventories and investigations.

Up to the time of the last data freeze (L1.2) the drilling activities in the Laxemar subarea, see Figure 2-2, comprised:

- Four approximately 1,000 m long cored boreholes (KLX03, KLX04, KLX05 and KLX06), although KLX05 and KLX06 where only preliminary mapped at the time of the data freeze.
- Several percussion-drilled boreholes with lengths ranging up to 200 m and reaching vertical depths down to 200 m.
- Several soil/rock boreholes through Quaternary deposits.

Furthermore, data from the already existing deep core-drilled boreholes KLX01 and KLX02, as well as data from the Simpevarp subarea (see SDM S1.2) were also available.

Borehole investigations during drilling of all core-drilled and percussion-drilled boreholes were carried out according to a standardised programme, see SDM L1.2 for details. The borehole investigations performed following the drilling of the boreholes can broadly be divided into logging, detailed mapping, rock stress measurements, hydraulic measurements, sampling of rock and fractures for determination of density, porosity, magnetic susceptibility, mineralogy, geochemistry, diffusivity, sorption properties, rock strength and thermal properties, and groundwater sampling for the hydrogeochemical analyses.

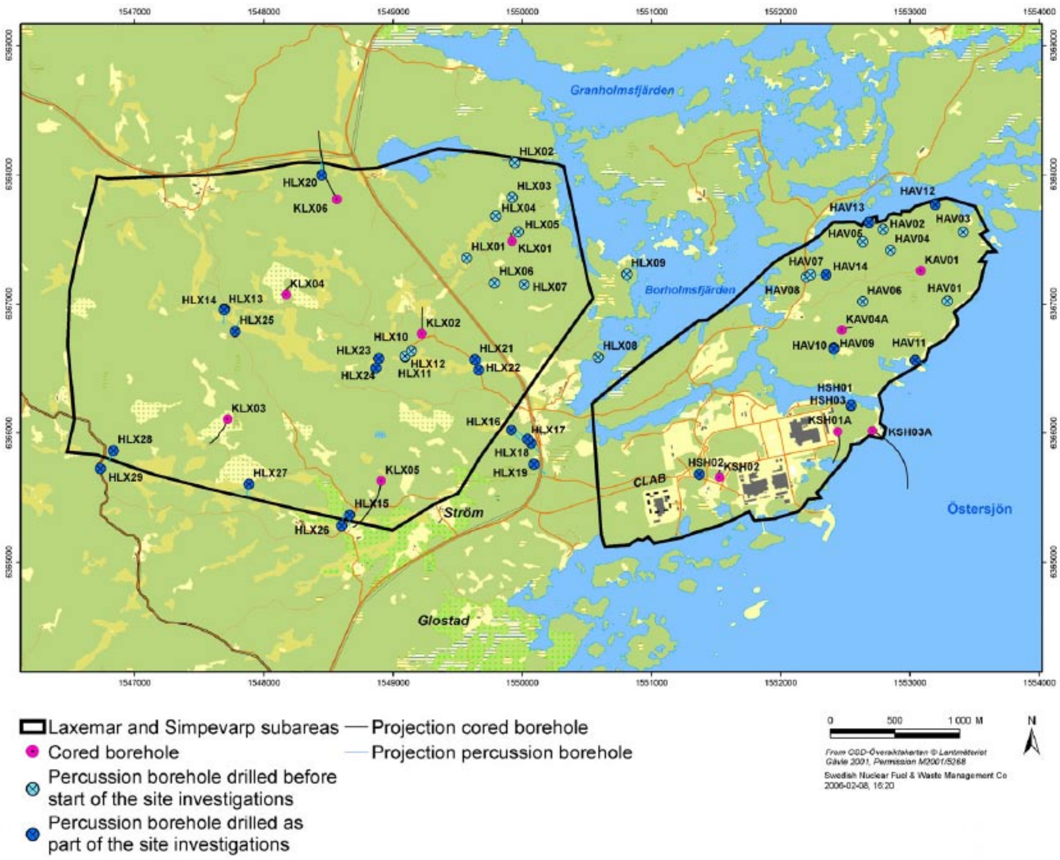

***Figure 2-2.*** *Overview map of the locations of core-drilled and percussion-drilled boreholes in the Laxemar and Simpevarp subareas. (Figure 2-3 in SDM L1.2)*

Other relevant data sources are “old” data that are either already stored in relevant official SKB databases, or are listed in the version 0 report /SKB 2002b/ and remain to be input into the databases. One obvious extensive source of information is that provided by the characterisation data and associated descriptive models available from the Äspö Hard Rock Laboratory (Äspö HRL). The position taken by the site descriptive modelling project is to make use of selective information important for filling voids in the data needs of the modelling process. The ambition is by no means to integrate the vast Äspö HRL database in its entirety. Examples of data of interest from Äspö HRL are various generations of geological data, models of deformation zones and various compilations of hydraulic test results that have been used when developing the geological and hydrogeological site-descriptive models. Likewise, compilations of transport properties relevant to Äspö conditions (and the associated data on geology/mineralogy) have been used in developing the bedrock transport models. Additional old data include surface and borehole information from investigations performed on the islands of Ävrö and Hålö. Old data are also available from the construction of the three nuclear power reactors on the Simpevarp peninsula (and associated tunnels and storage caverns). A third source of old data is related to the site characterisation and construction of the central storage facility for spent nuclear fuel (CLAB I and CLAB II).

All data are stored in the SKB databases SICADA and SKB GIS. The basic primary data are also described in the SKB P-series and R-series of reports. Full references to the reports and a more detailed description of the database are given in SDM L1.2.

### 2.1.2 The site descriptive model report

In the Site Descriptive Modelling, data are first evaluated within each discipline and the evaluations are then synthesised between disciplines. Three-dimensional modelling, with the purpose of estimating the distribution of parameter values in space, as well as their uncertainties, follows. The geometrical framework for modelling is taken from the geological model, and is subsequently used in rock mechanics, thermal, hydrogeological and hydrogeochemical modelling. The three-dimensional description presents the parameters with their spatial variability over a relevant and specified scale, with the uncertainties included in this description. If required, different alternative descriptions are provided.

The Site Descriptive Model Report, see SDM L1.2, first summarises available primary data and provides an overview of their usage, and then describes the development of the geosphere and the surface systems in an evolutionary perspective. Subsequent chapters in SDM L1.2 (Chapters 4 to 10) set out the modelling of surface ecology, geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry and transport properties, respectively. Each chapter provides the discipline-based accounts of evaluation of the primary data, three-dimensional modelling and discussion of identified uncertainties associated with the developed models. Chapter 11 presents the resulting descriptive model of the Laxemar subarea in a condensed form. Chapter 12 assesses overall consistency and confidence in the description. Chapter 13 provides the overall conclusions from the work.

### 2.1.3 Main features of the Laxemar subarea

This section outlines the main features of the Laxemar subarea as summarised in Chapter 13 of SDM L1.2. The text is provided for overview, and features of direct importance for the PSE are more thoroughly discussed in Chapter 3.

The topography of the Simpevarp area is characterised by a relatively flat topography (c. 0.4% overall topographical gradient), which largely reflects the surface of the underlying bedrock and is characterised by a high degree of bedrock outcrop (38%). Although flat, the landscape is interrupted by occasional narrow valleys, often associated with fracture zones in the bedrock. Till is the dominant Quaternary deposit which covers about 35% of the subarea.

The lithological domains defined in the Laxemar subarea, see Figure 3-1, are mainly domain RSMA primarily composed of Ävrö granite and dominating the northern and central parts of the subarea, domain RSMD consisting mainly of quartz-monzodiorite and a mixed domain RSMM (diorite to gabbro) dominating on the surface in the southwest and in an arc-shaped fashion dip to the north with the concave side to the north. A conspicuous rock domain (RSMP) is related to the north-easterly oriented set of shear zones that make up the eastern boundary of the subarea.

The bedrock in the Simpevarp area, which generally is well preserved and non-deformed, has been exposed to a series of tectonic events which has involved shifts in the direction and magnitude of compressional forces exerted on the rock mass. The distributional pattern of deformation zones, see Figure 3-3, is different between the Simpevarp subarea, where the major deformation zones largely align with the belt of shear zones, and in the Laxemar subarea, where there is a strong element of NS and EW zones. The characteristic ductile features in the Simpevarp area are the occurrences of low-grade brittle-ductile shear zones comprsing the northeasterly belt of zones associated with deformation zones ZSMNE005A (Äspö shear zone) and ZSMNE004A, which also make up the rock domain RSMP discussed above.

Compared with the Simpevarp subarea, which is located within a belt of shear zones, the Laxemar subarea is set in a more tectonically stable environment. However, as usually observed in crystalline rock, statistical analyses of rock mass fractures between deformation zones indicate a large spatial variability in the size, intensity and properties both between and within the different rock domains. The derivation of fracture orientations has revealed five sets; three regional sets and two local sets typical to each subarea.

Thermal conductivity varies in space at various scales and is also generally rather low. This can be attributed to the low and varying quartz content of the different rock types making up the bedrock.

The intact rock shows intermediate strength and it also depends on rock type. Rock stresses could be separated into two different stress domains. Stress domain II shows relatively low stress levels whereas higher levels prevail in Stress Domain I.

Analyses of the hydraulic test data, from deformation zones and the intervening rock mass show indications of conductivity decreasing with depth, both in the deformation zones and in the intervening rock mass. There is also an indication that conductivity varies with lithology. However, the few borehole data and the strong variability in hydraulic properties found in and between boreholes does not allow for a high degree of confidence to be established in the representativity of neither the depth dependence nor in the domain-related differences.

Four groundwater types have been identified in the Laxemar subarea, recent to young dilute waters found at shallow depths, brackish waters found at shallow to intermediate depths, more saline at intermediate to deep levels and highly saline (only seen in KLX02 at depths > 1,200 m). The water composition is shown to be mainly consistent with the modelled evolution of the groundwater flow since the last Glaciation.

Measurement data from the laboratory on core samples as well as down-hole measurements of the formation factor $F_f$. have been used to parameterise a retardation model that considers the transport properties of the major rock domains as well as the properties of different types of fractures with focus on the Laxemar subarea. A major improvement in the current site descriptive model is the inclusion of sorption data for a larger set of nuclides, representing a wider range of sorption properties, than was available for the previous model version. Furthermore, first-order estimates of the flow related migration properties (transport resistance F) are now provided in the site descriptive model.

### 2.1.4 Overall confidence in the modelling

The understanding of the Laxemar subarea is addressed and discussed in Chapter 12 of the SDM L1.2, where the identified uncertainties of the developed discipline models are articulated and an overall confidence assessment is provided in the light of model interactions and integration. Chapter 13 sets out current conclusions as to the general understanding of the Laxemar area.

As discussed in Chapter 12 of SDM L1.2, most of the available data have been analysed and treated according to accepted practices. This also includes data arising prior to the initial site investigation phase. However, there are some biases in the data. The absence of gently dipping boreholes makes correction of fracture orientation biases uncertain and also raises concerns about the possibility of predicting the anisotropy of transmissive features. Data from the Äspö HRL suggests such anisotropy. There are also questions about the representativity of the rock mechanics, thermal, hydrogeological and hydrogeochemical samples. There are generally few data at depth from the rock domains where the potential repository might be located. These biases are hard to account for without getting access to more representative data.

Important steps in the modelling and more of the uncertainties are now quantified, or explored as alternatives. Notwithstanding, several hypotheses remain to be tested and some uncertainties remain to be quantified. Some uncertainties are related solely to the understanding of the site and do not have direct implications for safety assessment or repository engineering, whereas others have significant implications. Notably, these uncertainties mainly concern the thermal, rock mechanics and hydraulic properties of the rock between the deformation zones in the potential repository volumes. These important uncertainties will be further discussed in Chapter 3, and are not further discussed here.

Section 12.4 of SDM L1.2 demonstrates the integrated character of the Site Descriptive Modelling. By necessity, geology provides an important geometrical input in the model of rock domains, deformation zones and rock mass fracturing. Changes to the lithological model will could have a strong impact on most disciplines (e.g. rock mechanics, thermal and transport properties), although small changes of the geometrical dimensions of different rock domains may be of little consequence. Similarly, changes to the deformation zone model in particular influences the hydrogeological and rock mechanics models, although the details of the characteristics of the deformation zones surrounding the rock mass in the potential repository volume may have little importance for the flow inside this rock volume. Examples of feedback to geology are not that common yet, but exist. Interference test data currently relate to assessment of continuity in the surface parts of deformation zones. However, the domains of lower rock stresses assumed structurally controlled and support from measured stress data provide indirect support for relevant parts of the current deformation zone model. Another important interaction covered in the current work relates to the interplay between hydrogeology and hydrogeochemistry. The water composition is shown to be mainly consistent with the modelled evolution of the groundwater flow. Overall, the current discrepancies between the needed interactions and the interactions considered are not judged to be a major problem for confidence in the SDM version 1.2 of the Laxemar subarea. Overall, the Laxemar 1.2 site-descriptive model is also judged to be in agreement with the current understanding of past evolution.

No major surprises have been faced in the modelling in relation to what was known by S1.2. Changes of the Rock Domains are significant in the local scale model volume, particularly in Laxemar subarea. The rock domain model is definitely stabilising but will certainly be refined by use of forthcoming data from cored boreholes. The changes to the deformation zones in the Laxemar subarea mostly concern details, but there are still important uncertainties, since there are several medium and low confidence zones inside the Laxemar subarea. Partial support to the deformation zone model is provided by the alternative lineament interpretation made by an independent team. In contrast the modelling of the fracturing, thermal and hydraulic properties of the rock volumes between deformation zones in the potential repository volume is still not stable, due to few representative data from this volume.

## 2.2 Preliminary layout

The design premises and methodology for application in the preliminary design of underground excavations within the framework of SKB's site investigations is presented in "Deep Repository: Underground Design Premises. Edition D1/1", /SKB 2004c/. According to these design premises the goals of the design work during the Complete Site Investigations (CSI) are as follows.

- Present a facility description for the chosen site with a proposed layout for the final repository facility's surface and underground components as a part of the supporting material for an application. The description shall present an evaluation of constructability, technical risks, costs, environmental impact and the reliability and effectiveness of the operational phase. The underground layout shall be based on information from the CSI phase and serves as a basis for the safety assessment.

- Provide a basis for the Environmental Impact Assessment (EIA) and consultation regarding the siting of the final repository facility's surface and underground parts with proposed final locations of ramp and shafts, plus the environmental impact of construction and operation.
- Carry out the design work for the entire final repository facility to the point that it is possible to plan for the construction phase.

Ultimately, the design work should lead to a layout D2, to be used in the application for the Final Repository, which will be submitted after the CSI. The design premises, including the goals, will be updated before the D2 step is taken. An intermediate step in the design work is to carry out design step D1 after the Initial Site Investigation.

### 2.2.1 Methodology

For the design step D1 a design methodology is developed in the design premises document /SKB 2004c/. This has been applied to each site. The design methodology addresses several design tasks. Each task relates to a particular design issue. In a first step the following issues and tasks are addressed. (For further detail, see /SKB 2004c/, which also contain flow charts expressing the logical sequence for the assessment of the questions).

A: What locations and depths within the site may be suitable for hosting the final repository?

B: Is it reasonable to consider that the total required repository area can be accommodated, taking into account current respect distances to deformation zones and preliminary assumed losses of deposition holes because of local unfavourable geological conditions?

C: How can the deposition areas be designed with a view towards achieving sufficient space and long-term safety? With the sub-issues:

- C1. How can deposition tunnels, deposition holes and main tunnels be designed considering the equipment and activities that they are required to accommodate?
- C2. What distance may be required between deposition tunnels and between deposition holes in order to conform with the maximum permissible temperatures?
- C3. What orientation may be suitable for deposition tunnels taking into account both water seepage and mechanical stability in deposition tunnels and deposition holes?
- C4. How large a proportion of the deposition holes may be excluded as unusable during the excavation, based on the minimum permissible distance to fractures or fracture zones of too large a size, excessive water inflow and mechanical instability? How is the loss affected by different criteria for rejection?
- C5. Based on findings in steps C1 to C4 at what depth or over what depth range may it be suitable to build the final repository?

D: How can other underground openings, especially the central area's rock caverns, be designed to achieve stability and to accommodate the required equipment and activities?

E: How can the layout of the entire hard rock facility be configured?

The answers to these questions have potential safety implications, since the issues to be solved by the Rock Engineering team to a large extent concern adapting the layout in order to meet safety requirements and preferences.

Subsequent steps in the D1 design work concern engineering implications of the suggested design, like estimates of potential upconing and grouting needs. These issues could also have some safety implications, but assessing them is not part of the PSE, as further discussed in Section 3.8.

### 2.2.2 Applying the methodology to the Laxemar subarea

A type D1 design, reported in /SKB 2006b/ has been developed for the Laxemar subarea, see Figure 2-2. The design considers a repository for 4,500 canisters, based on current estimates of the final amount of spent fuel being produced in Sweden, but also assesses the space needed for an additional 1,500 canisters, in case the final amount of spent nuclear fuel should exceed current estimates. Layouts are presented both for the –500 m and –600 m levels. The possibility to adapt the layout to the interpreted deformation zones and the findings of the various assessments addressing question C, are presented and discussed in Chapter 3 of this PSE.

# 3 Analyses and comparison to criteria

This chapter summarises the analyses of the site data forming the basis for the PSE. These analyses have mostly been conducted within the Site Descriptive Modelling and the subsequent Rock Engineering design work and are fully described in associated reports.

## 3.1 Overview and means of evaluation

The PSE planning document identified a set of analyses to be undertaken in order to meet the objectives of the evaluation, i.e. to allow comparison with criteria and to provide feedback to Site Investigations and Rock Engineering. Most of these analyses have been conducted as a part of the Site Descriptive Modelling Version 1.2 /SKB 2006a/ and the subsequent Rock Engineering study /SKB 2006b/. The subsequent sections in this chapter summarise the main findings of these analyses.

### 3.1.1 Analyses considered in the PSE

Table 3-1 gives an overview of analyses used as a basis for the PSE. The table also provides an overview of analyses to be carried out in SR-Can and SR-Site. Especially as regards SR-Site, the table is preliminary, and will be updated based on the findings of the PSEs and SR-Can. In the planning document for the PSE, additional analyses, designed to provide further feedback to the continued investigations and site-specific repository design were envisaged. Omitting these analyses is judged to have negligible impact on meeting the objectives of the PSE. The analyses are important, but are more appropriately carried out at a later stage and so have been transferred to SR-Can or SR-Site, as further discussed in Section 3.8.

**Table 3-1. Safety related geosphere and biosphere analyses at various stages of the site investigation. The abbreviations in the columns indicate which of the three project groups involved in the site investigation will be responsible for the analysis; Site Descriptive Modelling (SDM), Repository Engineering (RE) or Safety Assessment (SA).**

| Type of analysis | PSE | SR-Can | SR-Site |
|---|---|---|---|
| **Thermal analyses** | | | |
| Thermal evolution of canister surface, buffer and near field rock | | | |
| – for present climate conditions | RE, SA | RE, SA | RE, SA |
| – for future climate conditions | No | SA | SA |
| Thermal evolution at the site scale | | | |
| – for present climate conditions | No | SA | SA |
| – for future climate conditions | No | SA | SA |
| **Hydraulic analyses** | | | |
| Groundwater flow calculations (and salinity evolution) at super regional, regional and local scales | | | |
| – for historic conditions | SDM | SDM | SDM |
| – for present climate conditions | SDM | SDM | SDM |
| – for future climate conditions | No | SA | SA |

| Type of analysis | PSE | SR-Can | SR-Site |
|---|---|---|---|
| Particle tracking for flow related migration parameters and discharge point distribution in the flow field | | | |
| – for present climate conditions | SDM/SA (Based on regional model and simplified layout) | SA, with layout according to D1 and using higher resolution. | SA |
| – for future climate conditions | No | SA (stylised cases) | SA |
| Drawdown and upconing analyses | No | RE, SA | RE, SA |
| Resaturation | No | RE, SE | RE, SA |
| **Mechanical analyses** | | | |
| Thermally induced rock stresses, considering inhomogeneous thermal rock properties | No | SA | RE/SA |
| Long-term, i.e. post closure, effects of rock mechanics events during construction and operation (including EDZ) | RE | RE/SA | RE/SA |
| Earthquake analyses, all time frames | Assessment of probability of deposition holes intersecting fractures RE, SA | SA | SA |
| Long-term stability, effects of glacial load | No | SA | SA |
| **Chemical analyses** | | | |
| Groundwater chemical evolution including colloids | | | |
| – historic and initial state | SDM | SDM | SDM |
| – future evolution (different scenarios) | No | SA | SA |
| Chemical evolution of buffer and canister | No | SA | SA |
| Backfill chemical evolution | No | SA | SA |
| Radionuclide speciation calculations | No | SA | SA |
| Assessment of ore potential | SDM | SDM | SDM |
| Influence of construction materials | No | SA | SA |
| Radionuclide transport analyses (geosphere) | | | |
| Transmission calculations and transport modelling | | | |
| – for present climate conditions | No | SA | SA |
| – for future climate conditions | No | SA (stylised cases) | SA |
| Colloid-facilitated transport | No | SA | SA |
| **Biosphere analyses** | | | |
| Near-surface hydrology | | | |
| – for present conditions | SDM | SDM | SDM |
| – for future climate conditions | No | SA (stylised cases) | SA |
| Biosphere model for radionuclide transport | | | |
| – for present conditions | No | SA | SA |
| – for future climate conditions | No | SA (stylised cases) | SA |
| Dose and risk calculations | No | SA | SA |

### 3.1.2 Basis of comparison

SKB has established criteria with which the properties of a candidate host rock will be compared /Andersson et al. 2000/. Some of these are absolute requirements whereas others are preferable conditions that would influence safety in a positive manner. The criteria are based on the state of knowledge and the repository design plans at the time when the criteria were formulated.

/Andersson et al. 2000/ also noted that new R&D results and/or a modified basic repository design could justify modifications to the criteria. For the purpose of this PSE, the criteria are still generally judged applicable. However, in some areas, the knowledge base has expanded. Therefore, after briefly presenting the previous preferences and criteria for each subject area, there is also a subsection providing conclusions from such additional considerations – if any. These additional considerations usually concern more specific/quantified rules or minor modifications of the previous criteria.

The assessment is made for each subject area, i.e. geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry and transport, following the outline provided in /Andersson et al. 2000/. After presenting the criteria and the additional considerations, the relevant findings from the Site Modelling /SKB 2006a/ and the design work /SKB 2006b/ are presented. Usually these analyses are sufficient to address the performance relative to the criteria, but in some instances some additional calculations, performed by the Safety Assessment team, are added. After presenting these various results, there is an evaluation of the degree to which the criteria and additional considerations are fulfilled with respect to safety, and what feedback may be given to the further Site Investigation and Repository Design work.

## 3.2 Geological features of relevance to safety

Geology provides the overall framework for the other geoscientific disciplines and is consequently indirectly of fundamental importance for safety. Furthermore, some geological characteristics, i.e. the nature and distribution of rock types, the location and characteristics of deformation zones and the fracturing, are of direct relevance for safety. These are assessed in this section.

### 3.2.1 Criteria and other safety considerations

#### *Previously set criteria*

The suitability criteria, as set out by SKB in /Andersson et al. 2000/, directly related to the geological description of the site, concern rock type distribution, deformation zones and fractures.

In order to mitigate the risk of future human intrusion, it is set as a *requirement* that the rock types in the deposition area do not have ore potential and do not contain such valuable minerals as to justify mining at a depth of hundreds of metres. There is a preference for common rock types with no occurrence of valuable utility stone or industrial minerals. For the feasibility studies, this called for avoiding areas with known ore potential and heterogeneous or unusual bedrock. Furthermore, it was stipulated that, if extensive occurrence of ore-bearing minerals is encountered during the Site Investigation, the site should be abandoned.

Deformation zones are important to safety since they potentially could be re-activated, thus threatening the mechanical stability of the repository system. Usually they also have much higher hydraulic conductivity than the surrounding rock mass. Depending on their mode of formation, deformation zones can be ductile or brittle. Many ductile zones are in fact quite tight hydraulically, but some ductile zones could have been re-activated in periods of brittle deformation.

It was *required* that regional[1] ductile deformation zones are avoided, if it cannot be shown that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be tectonic lenses near regional ductile deformation zones that can be suitable for a final repository.

It was also required that deposition tunnels and holes may not pass through or be located near regional and local major brittle deformation zones and that used deposition holes may not intersect identified local minor fracture zones. Moderate densities (fracture surface area per unit volume) of fractures and of deformation zones shorter than 1 km are preferable. However, all these stipulations are now superseded by more recent considerations (see next subsection).

As a criterion for the Site Investigation, it is stated that if the repository cannot be positioned in a reasonable manner (would have to be split up into a very large number of parts) in relation to the regional and local major deformation zones, the site is not suitable for a final repository. However, at the time of publishing the suitability criteria document, no specific respect distances were defined. Such distances have now been developed, see below.

### *Additional considerations*

Since the issue of the SKB suitability criteria, there has been further evaluation /Munier and Hökmark 2004/ of the potential for shear movement and what might be prudent respect distances. The findings are also reported in the SR-Can Interim report (see /SKB 2004a/, Chapter 10). The findings are preliminary in the sense that they may be overly restrictive.

/Munier and Hökmark 2004/ have reported a number of simulations of secondary faulting induced by earthquakes, using different models. In particular, the simulations addressed the following question: "If a deformation zone near or within the repository reactivates seismically, how far from the source fault is the secondary slip on target fractures non-compliant with the limits of the canister failure criterion?" One aspect of the work is that it can be used to assess whether it is possible to avoid faulting exceeding a 0.1 m displacement across deposition holes by applying a "respect distance" with the following definition:

The respect distance is the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to potential future seismic effects on canister integrity.

The results of /Munier and Hökmark 2004/ have been used to define respect distances to be used in repository engineering and design. These are based on the condition that rapid shear movements at the deposition holes larger than 0.1 m could impair the integrity of the copper canister. Table 3-2 shows a summary of their findings and should be read as follows:
For each zone of a particular size, the half width of the deformation zone, including its transition zone, and the seismic influence distance are calculated, for earthquakes larger than M6. The respect distance is the larger of the two.

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[1] In the context of deformation zones, the expression "regional" zones relates to zones longer that 10 km, "local major zones" relates to zones in the length interval 1 to 10 km and "local minor zones" relates to zones in the length interval 10 m to 1 km , see /Andersson et al. 2000/. This nomenclature does not address properties of zones.

**Table 3-2. Seismic influence distance, for earthquakes larger than M6, and Deformation Zone half width in relation to zone length using various assumptions. The respect distance is the larger of the deformation zone half width and the seismic influence distance /from Munier and Hökmark 2004/.**

| Zone length | Seismic influence distance estimated from dynamic analyses of source to target interaction (calculated induced displacement should be < 0.1 m) | | Estimates of the half width of a deformation zone (including the transition zone). Actual zone (half) width should be used if known. | |
|---|---|---|---|---|
| | If > 100 m radius fractures avoided | If > 50 m radius fractures avoided | Zone half width estimated as 2% of zone length | Zone half width estimated as 1% of zone length |
| < 3 km | – | – | 0 m–30 m | 0 m–15 m |
| 3 km–10 km | 200 m | 100 m | 30 m–100 m | 15 m–50 m |
| > 10 km | 200 m | 100 m | > 100 m | > 50 m |

Table 3-2 implies that respect distances only need to be applied to deformation zones larger than 3 km, although for shorter zones it is still necessary to avoid the transition zones. It should be noted that this distance is the normal distance from the plane of the deformation zone, i.e. it is not restricted to the distance in the horizontal plane. Based on this table, Repository Engineering applies a minimum respect distance of 100 m to deformation zones larger than 3 km. Furthermore, in order to estimate the size needed for the repository, an assessment is made on how many potential deposition holes would need to be abandoned if a rejection criterion was applied to deposition holes intersecting excessively large fractures, as further discussed in Section 3.2.6.

The information in the table could also be used to estimate the potential for shearing of deposition holes in the context of a Safety Assessment. If the respect distance is set to a minimum of 100 m, only deposition holes intersecting fractures of a radius larger than 50 m would have any possibility of hosting a shear movement exceeding 0.1 m, but as further discussed by /Hedin 2005/ the maximum induced slip would only occur along minor portions of the reactivated fracture plane. Furthermore, on-going simulations /Fälth and Hökmark 2006/ demonstrate that, if fracture friction is also taken into account, in contrast to the friction-free assumption used in /Munier and Hökmark 2004/, the *size of discriminating fractures can be increased* from 50 m to 75 m in the band 100 m to 200 m away from the deformation zones and from 100 m to 150 m beyond 200 m. This is also the criterion applied in this PSE, in *contrast to the previous* ones for Simpevarp and Forsmark.

The number of deposition positions intersecting fractures larger than radius 75 m and 150 m, respectively, can be estimated from the discrete fracture network model as further discussed in Section 3.2.6. This number is an important input parameter to the risk assessment, but it should also be noted that the number of deposition holes actually affected will, for several reasons, be much less than this number.

SKB is currently exploring practical approaches to identifying potential deposition holes intersected by discriminating fractures. An important part of this identification is that features of radii exceeding 50 m usually are minor deformation zones and not single fractures. This means that, to a large extent, the discriminating features could be identified when they are intersected by a tunnel or a probe hole. Other possibilities for identification also exist. Most, if not all, deposition holes intersected by unfavourable fractures will be identified and not be used for deposition.

Furthermore, the impact on the canister will be less if it does not intersect the centre of the canister at a right angle. Additionally, only a few of the potentially problematic fractures will host slip exceeding the canister failure criterion. Finally, it is not certain that there will be an earthquake, sufficiently large as to trigger significant reactivation on fractures nearby, i.e. with M > 6, even on long time scales, although the probability is hard to estimate. These latter factors will be assessed in SR-Can, but are not addressed in this PSE.

### 3.2.2 Rock type distribution

According to SDM L1.2 (Chapter 3), the majority of the rocks at the present day erosional level in southeastern Sweden were formed during a period of intense igneous activity ca 1,810–1,760 Ma ago during the waning stages of the Svecokarelian orogeny. The dominant rocks comprise granites, syenitoids, dioritoids and gabbroids, as well as spatially and compositionally related volcanic rocks. This generation of igneous rocks belongs to the so-called Transscandinavian Igneous Belt (TIB). Locally, fine- to medium-grained granite dykes and minor massifs, and also pegmatite occur frequently. Though volumetrically subordinate, these rocks constitute essential lithological inhomogeneities in parts of the bedrock in the Oskarshamn region. After the formation of the TIB rocks, the next rock-forming period in southeastern Sweden, including the Oskarshamn region, did not take place until ca 1,450 Ma ago. It was characterised by the local emplacement of granitic magmas in a cratonized crust. In the Oskarshamn region, the ca 1,450 Ma magmatism is exemplified by the occurrence of the Götemar, Uthammar and Jungfrun granites.

In late Precambrian and/or early Cambrian time, i.e. ca 600–550 Ma ago, arenitic sediments were deposited and subsequently transformed to sandstones. The remainder of these formerly extensively occurring sedimentary rocks covers the Precambrian crystalline rocks along the coast of the Baltic Sea from the area south of Oskarshamn in the north to northeastern Blekinge in the south. Furthermore, during the ongoing site investigation in Oskarshamn, sandstone of presumed Cambrian age has been documented in a cored borehole. The sandstone occurs in a deformation zone and occupies ca 0.1 m of the drill core.

The bedrock history explains the rather complex lithology of the bedrock of the Laxemar subarea. According to SDM L1.2, it can be divided into the different rock domains displayed in Figure 3-1. (Figure 3-3 shows the surface expression of these domains). The rock domains have been given different codes where domains denominated with the same capital letter[2] are dominated by the same characteristics as displayed below:

- RSMA-domains: dominated by Ävrö granite.
- RSMB-domains: dominated by fine-grained dioritoid.
- RSMBA-domains: characterised by a mixture of Ävrö granite and fine-grained dioritoid.
- RSMC-domains: characterised by a mixture of Ävrö granite and quartz monzodiorite.
- RSMD-domains: dominated by quartz monzodiorite.
- RSME-domains: dominated by diorite to gabbro.
- RSMM-domains: characterised by a high frequency of minor bodies to small enclaves of diorite to gabbro, in particular Ävrö granite and quartz monzodiorite.
- RSMP-domains: characterised by a high frequency of low-grade ductile shear zones in the above mentioned rock types.

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[2] Physically separated volumes of the same rock domain character are given different numbers, e.g. RSMC01, RSMC02.

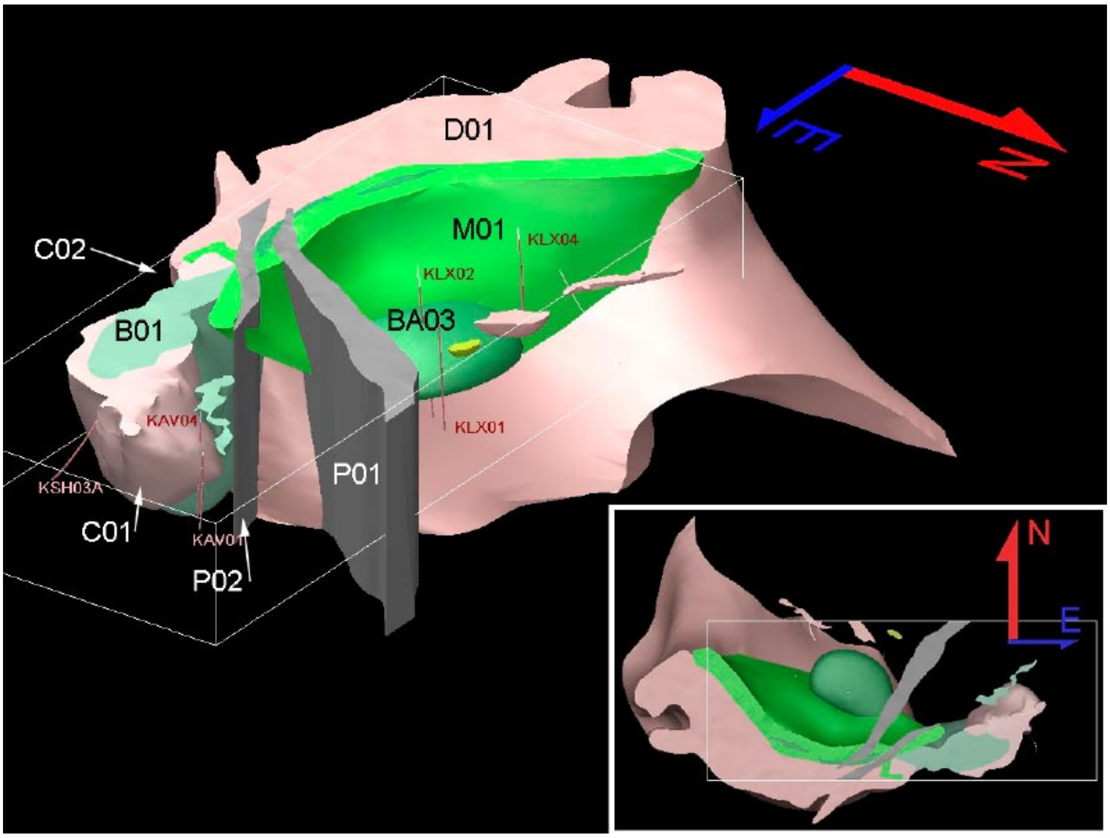

*Figure 3-1.* ***Figure 3-1.*** *Rock domain model, viewed from north east. Rock domains are indicated by short notation (i.e. B01, BA03, etc. where the number indicate different geometrical units of the same domain). Rock domain RSMA is unshaded in order to show some of the major three-dimensional characteristics. The local model volume and boreholes are also shown. It needs to be understood that the geometrical boundaries of the domains are uncertain, especially with depth. The insert shows the model from above. (Figure 11-2 SDM L1.2).*

Four of these domain types dominate the Laxemar subarea, as can be seen in Figure 3-1. RSMA, consisting mainly of Ävrö granite, dominates the northern and central parts of the subarea. RSMD consisting mainly of quartz-monzodiorite, together with a mixed domain RSMM (diorite to gabbro) dominates the surface in the southwest and in an arc-shaped fashion dip to the north with the concave side to the north. A conspicuous rock domain (RSMP) is related to the north-easterly oriented set of shear zones which make up the eastern boundary of the subarea. The latter domain is characterised by a high frequency of low-grade ductile to brittle-ductile shear zones in the rock types transacted by the low-grade ductile shear belts associated with deformation zones ZSMNE005A (Äspö shear zone) and ZSMNE004A, making up the domain. RSMP is thus not part of a potential repository volume.

The geometry in the 3D modelling is primarily based on the domain intercepts in the cored boreholes, but the modelled geometry is strongly supported by the geophysical modelling. In absence of reliable information, the southern boundary of the rock domain RSMD01 is modelled vertically towards the bottom of both the local and the regional model volume. However, the dioritoid dominated domains (RSMB and RSMBA) within the arc complex, have the shape of subvertical lenses oriented along the transitions between the above mentioned arc shaped major rock domains. Apart from being visually appealing, this finding is supported by a number of borehole observations. Apart from being lens shaped, it is anticipated that these domains follow the same trend at depth as the surrounding major rock domains.

Each rock domain has been assigned a set of properties including, for example, the dominant and subordinate rock types in the domain. All property tables are presented in an Appendix to SDM L1.2. For example, the variation in quartz content, being of importance for the thermal properties, in the quartz monzodiorite and the Ävrö granite in different domains is displayed in Figure 3-2. As can be seen the quartz content is generally low and the variation between the domains is substantial.

According to SDM L1.2, the following more significant uncertainties remain after the development of the rock domain model, version 1.2.

- Heterogeneity and proportion of subordinate rock types in the domains, i.e. veins, patches, dykes, minor bodies, frequency of minor deformation zones, are uncertain due to limited information. Proportions are given with the uncertainty expressed as ranges in the property tables, but there is no description of "size" distribution of heterogeneities, although indicator variograms from rock types have been assessed in the thermal modelling.
- Also the orientation of subordinate rock types, particularly fine- to medium-grained granite and pegmatite, is uncertain, again due to limited information. A great number of the documented fine- to medium-grained granites and pegmatites are not dykes in its formal geological definition, but display irregular shapes with no, or only weak, preferred orientation. The orientation could affect the anisotropy of the thermal properties.
- The spatial distribution of compositional variations of rock types – for example the Ävrö granite that are "rich" (granite to granodiorite) contra "poor" (quartz monzodiorite) in quartz is also uncertain. Subdivision of the Ävrö granite into a quartz-rich and quartz-poor variety is a natural step for upcoming model versions.
- The three dimensional distribution and character of alteration, e.g. oxidation (red staining), saussuritisation, sericitisation and chloritisation (hydrothermal alteration) are uncertain. There is limited information and it is difficult to estimate the proportion, spatial distribution and not the least the degree ("strength") of alteration. However, these alterations are judged to usually imply increased thermal conductivity, i.e. ignoring these alterations results in underestimates of the thermal conductivity. The uncertainty is expressed as proportions with uncertainty.

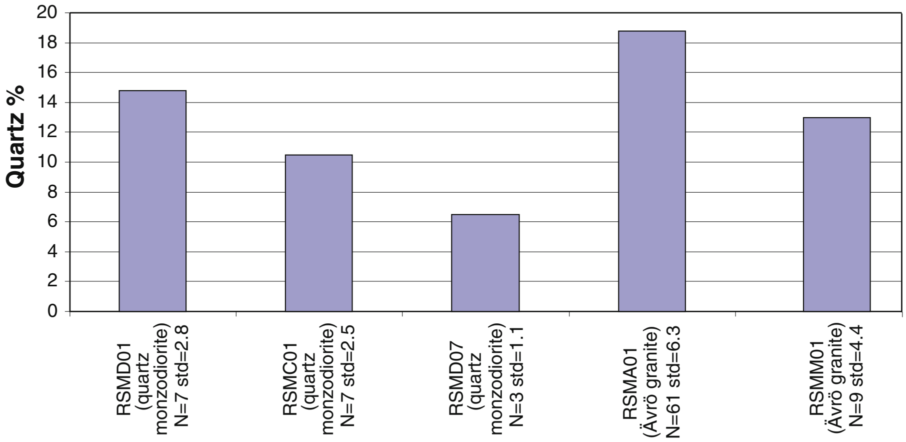

***Figure 3-2.*** *Quartz content (mean value) in quartz monzodiorite in RSMD01, RSMC01 and RSMD07, and in Ävrö granite in RSMA01 and RSMM01. N is the number of samples and std sample standard deviation. (Figure 5-52 of SDM L1.2).*

Overall, there are no surprises in the Rock Domain model. Compared with Simpevarp version 1.2, the changes of the Rock Domains are significant in the local scale model volume, particularly in Laxemar subarea and in the area in between the latter and the Simpevarp subarea. The rock domain model is definitely stabilising but will certainly be refined by use of forthcoming data from cored boreholes obtained in the Complete Site Investigation.

### 3.2.3 Assessment of ore-potential or other potentially valuable resources

The potential for ore, industrial minerals and commercial stones of the site has been assessed by an experienced exploration geologist (/Lindroos 2004/, see also Section 5.3.5 in SDM L1.2). In that work, ore potential was defined as mineralisations considered worthwhile exploring today or over a longer period. It is concluded that the Simpevarp regional model area is dominated by intrusive rocks and granites, belonging to the ca 1,810–1,760 Ma generation of the Transscandinavian Igneous Belt (TIB), which by experience is more or less devoid of metallic mineralisation. The only candidate for metallic mineralisation in the Simpevarp regional model area is the ca 1,450 Ma old Götemar-type granite, which is judged to have a potential for tin (Sn) and tungsten (W), although no mineralisations of this type have so far been found.

Consequently, the whole Simpevarp regional model area may be considered as sterile concerning metallic mineralisations and ores. Furthermore, the only real potential for quarrying building- and ornamental stone is associated with the Götemar and Uthammar granite intrusions in the north and south, respectively, i.e. well outside the Laxemar subarea.

### 3.2.4 Deformation zones and fractures

#### *Deterministic Deformation Zones*

The base case deformation zone model of the Laxemar subarera consists of high, medium and low confidence deformation zones, see Figure 3-3 and Figure 3-4. All deformation zones included in the base case model are considered to exist, although the degree of confidence for zones that have no direct observations is lower. Structures that are considered to be shorter than 1 km within the local area are handled through a statistical approach and are presented as part of the fracture statistical description, see next section.

Thirty-five deformation zones in the regional model domain (modelled in 38 segments) have been interpreted with a high confidence in their existence. Each one of these interpreted zones is observed both indirectly, through lineament or geophysical data, and directly through field mapping, borehole or tunnel observations. Exceptions are the Mederhult zone (ZSMEW002A), Zones ZSMNS009, -10 and -11, which have not been observed in boreholes or tunnels but have been observed in field mapping, or have such a major regional imprint in the topography, magnetic map or through clear anomalies in geophysical profiles that their existences are considered being of high confidence. Also, a few high confidence zones have been based solely on indirect surface observations in combination with strong evidence from seismic refractions or reflections. For more detail, see Table 5-5 of SDM L1.2. One hundred and fifty-five (N=155) medium and low confidence zones have also been included in the deformation zone model. Of these, sixty-two (N=62) are of medium confidence.

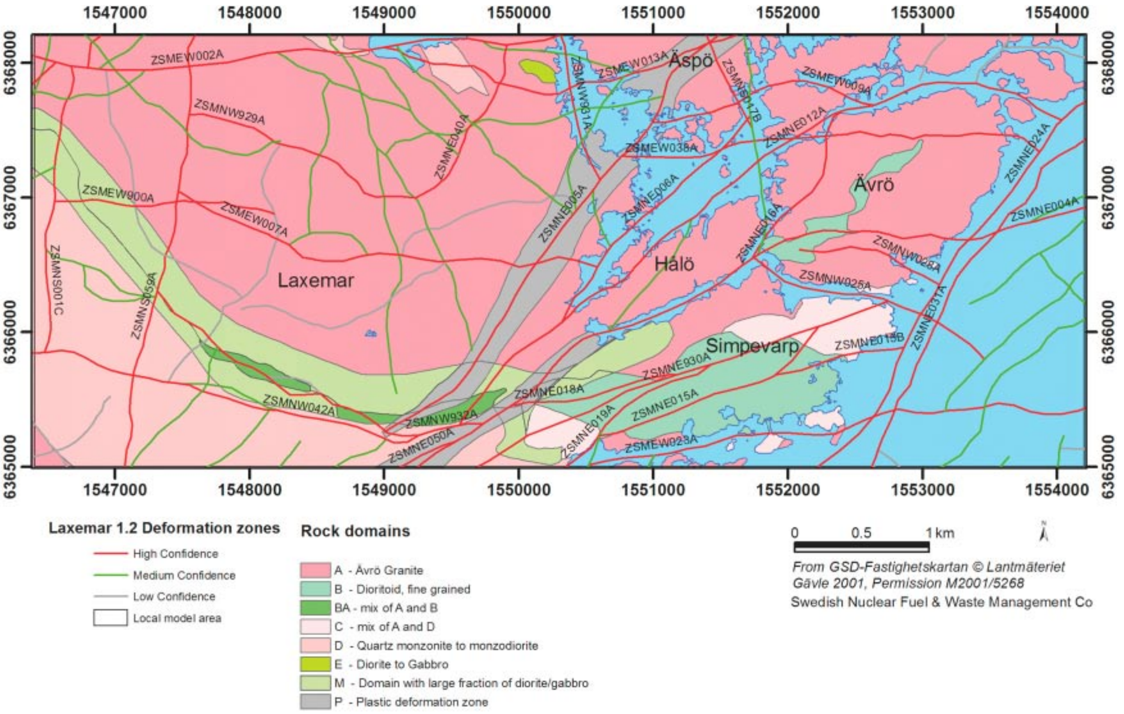

***Figure 3-3.** Illustration of the base case deformation zone model with high (red), medium, (green) and low (grey) confidence zones within the local model area. The alternative deformation zone model consists only of the high and medium confidence (red+green) deformation zones. (Figure 11-4 in SDM L1.2).*

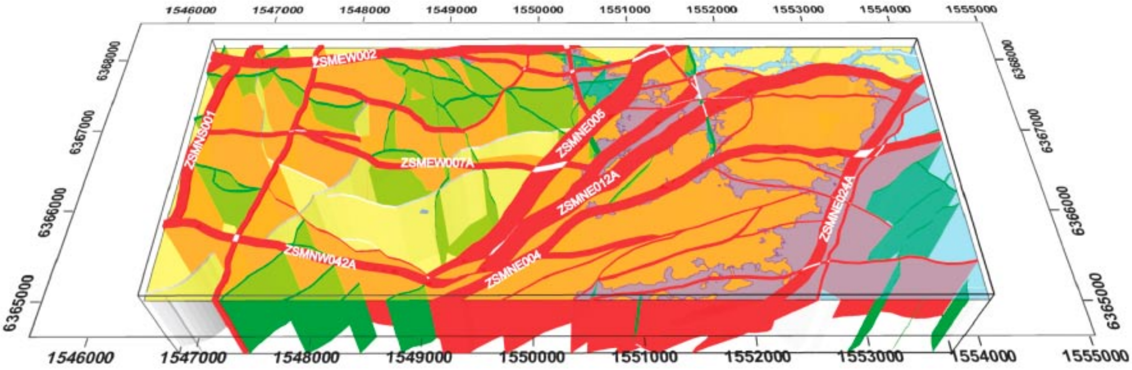

***Figure 3-4.** Local scale model of deformation zones.. Red, green and grey indicates high, medium and low confidence zones respectively. (Figure 11-6 of SDM L1.2).*

For the most part the Simpevarp 1.2 model /SKB 2005c/ interpretations of deformation zones in the Simpevarp subarea are retained. Most changes to the model have been made to zones in the central parts of the Laxemar subarea, involving geometry (dip and extent) and degree of confidence. A new entity in L1.2 is the subhorizontal zone (ZSMNW928A) interpreted from reflection seismics and borehole data, which is shown to be located well below typical repository depth (> 770 m) in the central parts of the Laxemar subarea. Additional support to the general validity of the underlying lineament map is provided by an independent alternative lineament interpretation /Korhonen et al. 2005/. The interpretations are general similar although there are some differences in details.

Overall, the uncertainties in the deformation zone model can be summarises as follows, see Sections 5.4.5 and Section 12.3.2 of SDM L1.2.

- Most local major, steeply dipping zones have been identified at the surface. The lineament interpretations performed by two separate teams show good correlation, which enhances confidence in the model.
- Potentially there are deformation zones not included in the model. This mainly relates to sub-horizontal zones as these are harder to detect. However, it is clear that gently dipping regional zones do not exist within the local model domain, but there is generally a lack of any possibility to secure data from local major and local minor gently dipping deformation zones at a large scale. A few gently dipping deformation zones have been proposed and included in the geometric framework based on seismics.
- The continuity, and thus the size estimate, along strike and dip at depth and the termination of the deformation zones are uncertain.
- Clear surface anomalies (topography, magnetic, EM) tend to be more complex at depth (in boreholes) – i.e. ZSMEW007A type zones.
- The character and properties of the zones are uncertain, also in the well-established high confidence zones. There is a strong spatial variation of properties (width, internal structure, fracturing, and hydraulic properties) as seen in a few cases where there are multiple borehole intercepts in a zone. The information density is limited, with inherent concentrations of data where the zones are intersected by the surface or by boreholes. Zones rated as high confidence include uncertainty description based on all supporting data.

In summary, there are still important uncertainties in the deformation zone model of the Laxemar subarea, and this is also expressed by the fact that there are several medium and low confidence zones inside the subarea. It should also be noted that most lineaments at Laxemar when further explored were shown actually to be deformation zones, i.e. most of the medium confidence zones are most likely real zones (although uncertain in properties and extent).

### *Statistical Discrete Fracture Network (DFN) Model*

Smaller zones and fractures, not covered by the deformation zone model are handled in a statistical way through DFN models. The descriptions are based on fracture observations in the boreholes, mapped fractures at outcrops and from interpretation of lineaments.

The stochastic DFN model is described in detail in /Hermanson et al. 2005/ and outlined in Section 5.5 of SDM L1.2. The conceptual framework of the model was derived from statistical testing of initial hypotheses concerning different aspects of the model geometry and the geological controls on that geometry. There are several assumptions that have been made in order to construct the DFN model:

- Assumption 1: The length of a deformation zone trace or a fracture in outcrop is an accurate and appropriate measure of a single fracture's trace length for the purpose of deriving the radius distribution of geologic structures.
- Assumption 2: If a fracture set in outcrop represents a size-censored portion of a population of fractures that include a deformation zone-related trace set, then the fracture set in outcrop should have the same orientation as the deformation zone set. Conversely, the similarity in orientation is evidence in support of (however in-conclusive) combining the two separate groups of traces into a single set.

- Assumption 3: There is a 'tectonic continuum' between the outcrop-scale features (fractures) and the regional-scale structures (kilometre-scale deformation zones). Some of the outcrop fracture patterns constitute a small-scale expression of regional features. The size calculation for deformation zone-related sets is based upon fitting a power law curve to the combined data set of deformation zone and outcrop fracture trace lengths.
- Assumption 4: Variations in fracture intensity as a function of rock type, alteration zone or any other geological control can be extrapolated from sampled boreholes and outcrops to yet unsampled parts within the same rock domain.
- Assumption 5: For the Laxemar 1.2 DFN model, it is assumed that the fractures can be approximated as planar, circular discs. No statements are made regarding the aperture (width) or hydraulic properties of the DFN fractures.

The resulting DFN-model for Rock Domain A in the Laxemar subarea is summarised in Table 3-3 and Table 3-4. The DFN-model size and intensity parameters are coupled and reported as $r_0$, $k_r$, $P_{32}$ triplets for the regional fracture sets. The proposed size model for domain A in the Laxemar subarea can hence be reproduced from /Hermanson et al. 2005/ as in Table 3-3. /Hermanson et al. 2005/ also present DFN-models for the other rock domains

The orientation parameters intended for use within SR-Can are reproduced from /Hermanson et al. 2005, Table 7-4/.

**Table 3-3. DFN size model for SDM L1.2 compiled from /Hermanson et al. 2005, Tables 7-5 and 7-6/, who also provide notation and more detail.**

**SIZE** **Date: 2005-11-18**
**LAX_DFN_1.2_SIZ_rev5.0**
**Laxemar Sub-Area, Domain A**

| Set name | Probability Distribution | $k_r$ (Mass) | $k_r$ (Euclidian) | $r_0$ | $P_{32}$ |
|---|---|---|---|---|---|
| S_A | Power Law | 2.86 | 2.85 | 0.328 | 1.310[a] |
| S_B | Power Law | 2.92 | 3.04 | 0.977 | 1.026[a] |
| S_C | Power Law | 2.88 | 3.01 | 0.858 | 0.974[a] |
| S_d | Exponential | – | – | 4[c] | 2.32[b] |
| S_e | Power Law | 3.6 | N/A | 0.400 | 1.40[b] |

[a] From table 7-5 in R-05-45.

[b] From table 7-6 in R-05-45.

[c] Refers to the parameter l of the exponential distribution. The mean and standard deviation are both equal to 1/l.

**Table 3-4. DFN orientation model for SDM L1.2.**

**ORIENTATION ALTERNATIVE 1** **Date: 2005-05-03**
**LAX_DFN_1.2_ORI_rev2.00**
**Laxemar Subarea**

| Set Name | Probability Distribution | Mean Pole Trend | Plunge | Dispersion κ | Goodness of Fit K-S | % Sig. |
|---|---|---|---|---|---|---|
| S_A | Univ. Fisher | 338.1 | 4.5 | 13.06 | 0.031 | 55.60% |
| S_B | Univ. Fisher | 100.4 | 0.2 | 19.62 | 0.058 | 10.70% |
| S_C | Univ. Fisher | 212.9 | 0.9 | 10.46 | 0.076 | 15.70% |
| S_d | Univ. Fisher | 3.3 | 62.1 | 10.13 | 0.021 | 99.70% |
| S_f | Univ. Fisher | 243.0 | 24.4 | 23.52 | 0.216 | N/S |

A verification exercise has been performed to examine to what extent the geological DFN model for the Laxemar 1.2 local model domain is consistent with characteristics measured on outcrops and in boreholes. In the simulated borehole exploration, DFN realisations were sampled over 25 m borehole sections and on outcrops of similar sizes to the mapped outcrops. The results are displayed in Figure 3-5, and the following can be observed:

- Fracture orientations and the spatial distribution of simulated outcrops are similar to observed data.
- Total simulated fracture intensity ($P_{21}$) in outcrops is overestimated.
- Total simulated fracture frequency in 25 m-borehole sections ($P_{10}$) is underestimated.
- Variability in simulated fracture frequency in 25 m-borehole sections ($P_{10}$) is underestimated.

As discussed in Chapter 5 and Chapter 12 of SDM L1.2 and the supporting document /Hermanson et al. 2005/ there are several uncertainties in the DFN Model. The verification exercise clearly indicates some of these uncertainties. Possibly, the most important uncertainties concern the fracture intensities and the size distribution of the subhorizontal sets.

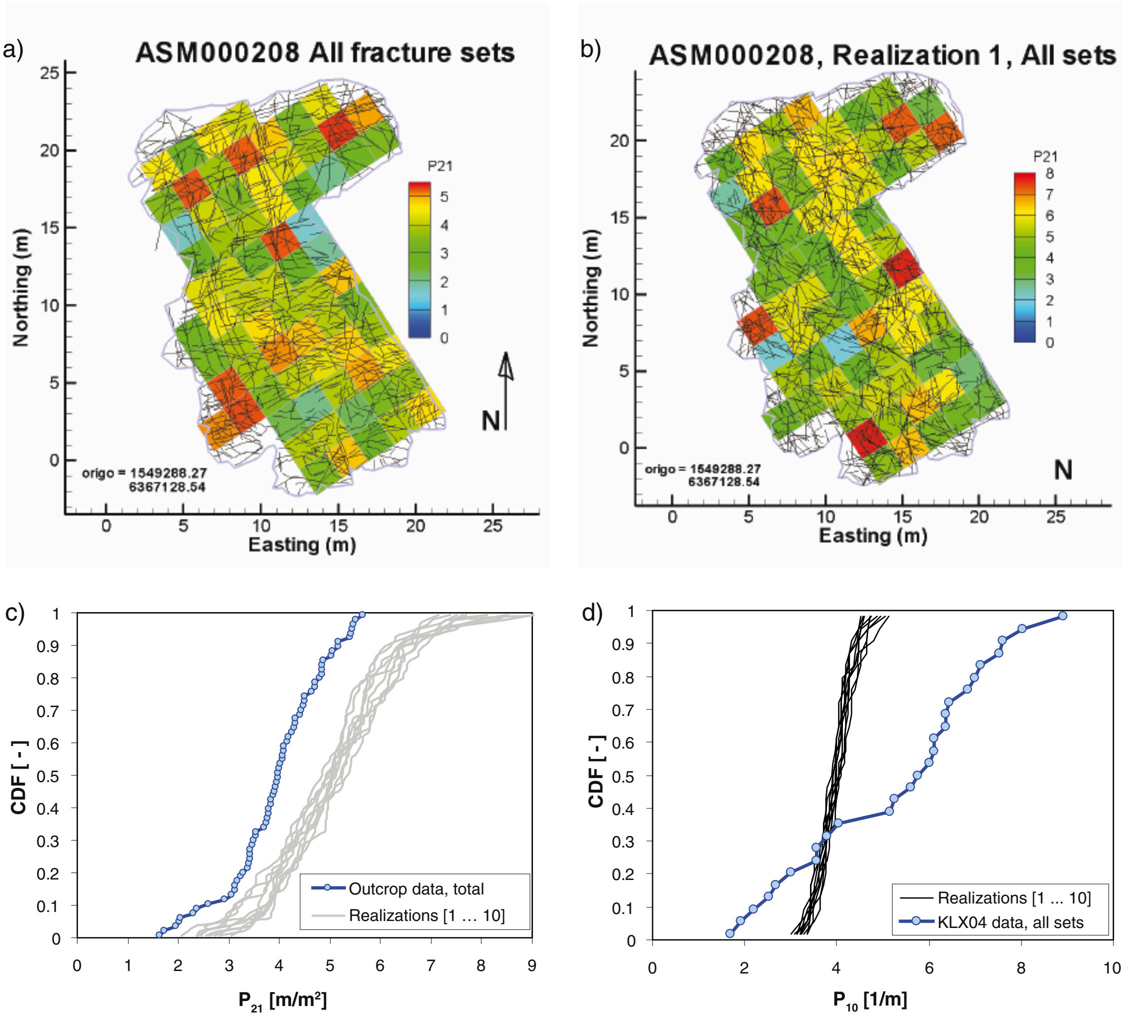

***Figure 3-5.*** *Evaluation of Laxemar subarea, RSMA, all fracture sets. Traces of outcrop ASM000208 compared to one realisation. Simulated fracture properties (grey lines) are compared to field data (blue), in terms of: fracture intensity, $P_{21}$ and fracture frequency (Figure 5-79a–d of SDM L1.2).*

- The fracture intensity and its variability are uncertain. The current assumption is that fracture intensity is dependent on Rock Domain, but there is a high variability in borehole fracture intensity, also in sections not identified as deformation zones. A more stable model could possibly be obtained by applying different geological controls, such as dividing the DFN-model into smaller subdomains based on lithology, alteration or closeness to deterministic zones. Systematic variability with depth has been tested and rejected. There is a need for understanding the difference between potential volumes in the rock having anomalously high fracture intensity and the increased intensity inside local minor deformation zones. A possible alternative is a fractal spatial model for background fractures coupled with a system for identifying local minor deformation zones in boreholes.
- Another uncertainty concerns the size distribution of the sub-horizontal set. There are few, if any, possibilities to observe the traces of this set. It is also uncertain whether the sub-horizontal fracture sets found in outcrop and boreholes like the vertical sets are part of a parent subhorizontal fracture set that has some members with radii of hundreds or thousands of meters. However, since the horizontal fractures do not show mineralogical or morphological differences from the vertical sets, it seems more likely than not that these horizontal fractures do extend in size to hundreds or even thousands of meters.

The above uncertainties and potential alternatives have *not* been fully developed for SDM L1.2. Furthermore, even though the model suggests there are differences between rock domains, there are few borehole data from these rock domains within the potential repository volume. For this reason this PSE only addresses the implications of the DFN-model as given by Table 3-3 and Table 3-4. This gives an indication of the implications of the fracturing at the Laxemar subarea, but will of course not be a sufficient bound of the uncertainty in the DFN-model for later use in SR-Site. Then, a thoroughly updated DFN-model with uncertainty bounds will be used.

### 3.2.5 Layout adaptation to deformation zones

#### *Deposition volumes*

For deformation zones longer than 3 km, the repository layout developed in the D1 design work for the Laxemar subarea /SKB 2006b/ applies a respect distance equal to the zone width, including the transition zone, or at least 100 m, i.e. in accordance with the rules defined in Table 3-2. For zones shorter than 3 km, a margin for construction is applied that equals the zone width plus a safety margin, in principle individually set for each deformation zone, based on potential construction problems, i.e. the applied rule is somewhat stricter than the safety related respect distance as given by Table 3-2. Figure 3-6 shows resulting respect distances, indicating potentially available deposition areas, at the –500 m level. Both high and medium confidence zones are considered. The impact of low confidence zones is assessed in a sensitivity analysis.

The area of the rock actually needed for the repository depends on the number of canisters, the thermal properties of the rock and the "degree-of-utilisation". The latter depends on the mechanical stability, the probability of deposition holes intersecting fractures or deformation zones with radius R > 50 m, and the inflow of water to tunnels and deposition holes, see the design premises document /SKB 2004c/. As already mentioned in Section 2.2, the premises of the design work were for 4,500 canisters plus space for an additional 1,500 canisters.

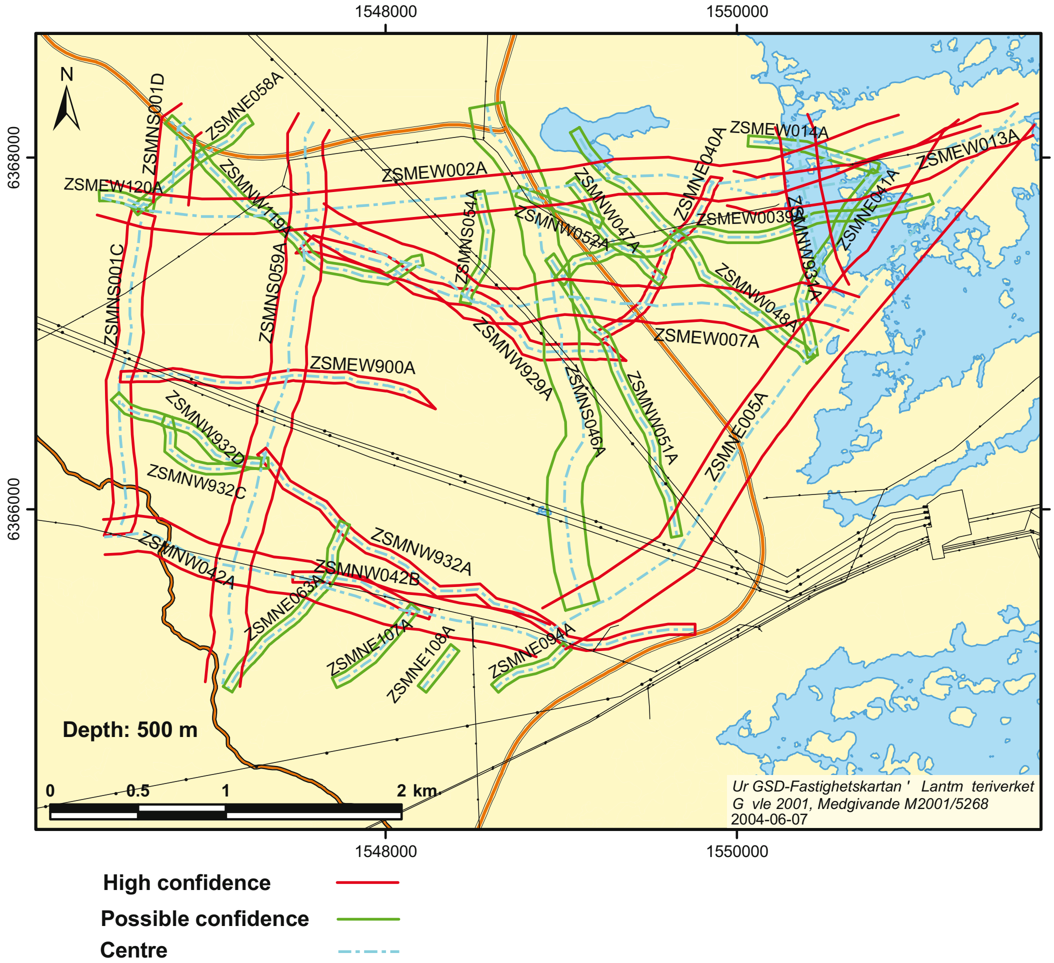

*Figure 3-6. Respect distances from the large (> 3,000 m) high (red) and medium (green) confidence deformation zones at the –500 m level. (From /SKB 2006b/).*

Using this information, the modelled thermal properties and the assessment of degree of utilisation the layout D1 design work for the Laxemar subarea /SKB 2006b/ presents potential layouts adapted to the respect distances. Figure 3-7 shows a potential layout at the –500 m level. Due to the negligible risk of spalling in the deposition tunnels, see Section 3.3.3, tunnel orientations are selected to make best use of available space without consideration of stress orientation. At this level the degree of utilisation is estimated to lie between 75 and 80 percent. Layouts at the –600 m level have also been developed and those need about the same area, but the degree of utilisation decreases to 50 to 60 percent, due to expected problems of rock spalling in deposition holes. It should also be remembered that the potential repository layouts presented for the Laxemar subarea are based on the current Site Description. Later versions of the layout will need to incorporate any modifications of the Site Description, including changes of the deformation zone geometry.

The layout D1 design work for the Laxemar subarea /SKB 2006b/ also presents a limited sensitivity study varying the length of some deformation zones (affecting whether they have respect distance or not), varying the degree of utilisation for various reasons, varying the dip of the deformation zones in accordance with the uncertainties provided in the SDM L1.2 and varying the distances between deposition holes and deposition tunnels (based on different assumptions concerning mean thermal conductivity).

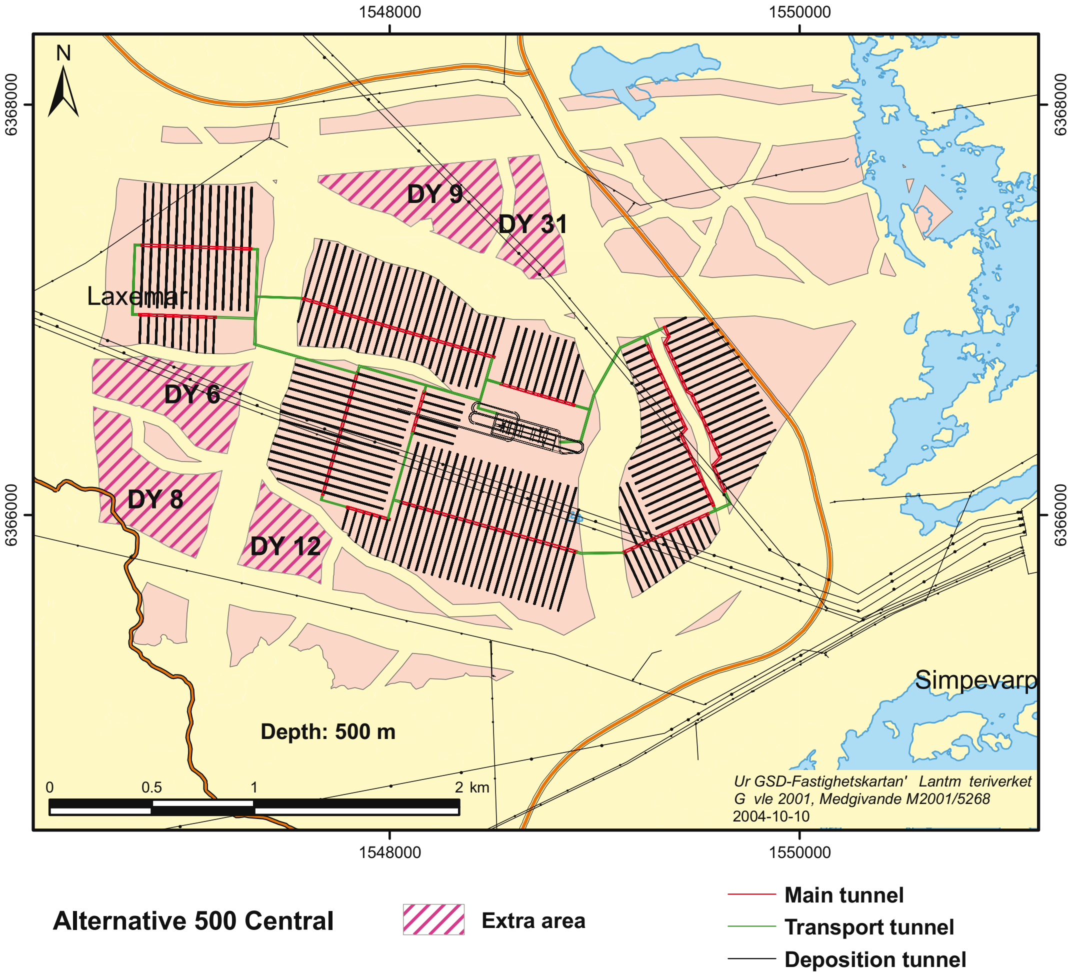

***Figure 3-7.** Potential Layout at the –500 m level. Due to the negligible risk of spalling in the deposition tunnels, tunnel orientations are selected to make best use of available space without consideration of stress orientation. (From /SKB 2006b/)*

Of these changes, the change in thermal conductivity, potential increase in loss of deposition hole positions and the inclusion of low confidence deformation zones has a large impact on the available space. In contrast, changing the orientation of the high-confidence and intermediate confidence deformation zones affects the geometry of the base layout, but has no or little impact on the available space. Given the size of the Laxemar subarea, it is nevertheless found that there is sufficient space, with margin to host a repository within the subarea.

### 3.2.6 Probability of deposition hole intersections with fractures and deformation zones

According to the respect distance rules summarised in Table 3-2, impacts of glacially induced faulting would only be an issue in deposition holes intersected by fractures (or deformation zones) with radii exceeding 75 m (for a 100 m respect distance) or 150 m (for a 200 m respect distance). From this the following three issues arise.

- What is the percentage of deposition holes that potentially could be intersected by fractures larger than the critical size? The answer to this question, together with an assessment of the probability of identifying the deposition holes with fractures larger than the critical size, is direct input to the Safety Assessment risk calculation.

- If a design rule for discarding deposition hole positions is adopted, what would be the impact on the degree of utilisation, given that the design rule would need to err on the side of caution, whether a deposition hole is intersected by a fracture larger than the critical size? The answer to this question has implications for design.
- If a design rule is applied for discarding deposition hole positions, how successful would it be?

The method described in /Hedin 2005/ is applied for addressing the first two of these questions. The method is analytical, verified by numerical simulations, and is based on the particular types of statistical descriptions of fracture sizes and orientations that emerge from the site investigations. Furthermore, the analysis is based on the full fracture population i.e. the DFN-parameters representing both "open" and "sealed" fractures. The final question is being addressed in an ongoing study by SKB.

### *Probability of canister intersections estimated by safety assessment*

The issue of large fractures intersecting deposition positions is different from the perspectives of design and long-term safety. For design the issue is the impact on degree of utilization if potential deposition holes need to be discarded. From the point of view of long-term safety, the issue is to determine the risk of *deposited canisters actually being intersected by discriminating features*. (Furthermore, also the small probability of an earthquake of M > 6 needs to be considered). If it is pessimistically assumed that none of the discriminating fractures can be detected (i.e. if the design rule were ineffective) what is then the likelihood that a randomly emplaced canister would be intersected by a discriminating fracture?

The calculated fraction of *canisters* being intersected by discriminating fractures, $\varepsilon$, of radius larger than 75 m is about 2.7 percent using parameter values from the geological DFN model of rock domain A, as described in Table 3-3[3] and Table 3-4 and the method referred to above. It is emphasized that $\varepsilon$ is the expected fraction of canisters intersected by discriminating fractures if no deposition positions are discarded. In reality, a substantial number of these positions are expected to be identified and not utilised.

The preliminary layout is based on a respect distance of 100 m. This requires deposition holes located within a band 100 to 200 m from a deformation zone capable of hosting a major earthquake to be discriminated if they are intersected by fractures with radii exceeding 75 m (minimum fracture radius in Table 3-5). Deposition holes positioned more than 200 m from any deformation zone are discriminated if they are intersected by fractures with radii exceeding 150 m, see 3.2.1 for details. The 2.7 percent of canisters intersected refers to positions in the 100 to 200 m band. For positions farther away from the large deformation zones, the corresponding figure is 0.5 percent.

The fractures of interest, from this perspective, are those that are assumed not to be readily detectable in deposition tunnels or otherwise. In the present calculation, all fractures with radii exceeding 250 m (maximum fracture radius in Table 3-5) are assumed to be readily observable. Increasing the maximum fracture radius to 500 m increases the number of intersected positions by roughly twenty percent. This is a non-significant increase considering the overall uncertainties, i.e. fractures with radii in the interval 250 to 500 m do not contribute substantially to the number of intersected positions.

---

[3] According to /Hermanson et al. 2005/, the $k_r$-values denoted "Euclidian", in Table 3-3 are the most representative for a model scale exceeding 30 m, otherwise those denoted "Mass" should be used. Since fractures of sizes exceeding 50 m are considered here, the "Euclidian" $k_r$-values are used. For the S_e set, however, the "Mass" value is used because of lack of a "Euclidian" value. The two types of values are related to whether fracture data are extrapolated linearly (Euclidian) or non-linearly (Mass) when constructing the DFN models. According to /Hermanson et al. 2005/, the "Mass" model for the S_d is only weakly non-linear, supporting the use of the "Mass" value for the S_d set.

**Table 3-5. Data, additional to the geological DFN data, required for the calculation of the fraction of intersected canisters.**

| | |
|---|---|
| Canister radius | 0.525 m |
| Canister height | 4.83 m |
| Minimum fracture radius | 75 m |
| Maximum fracture radius (larger fractures assumed trivially observable and thus avoided) | 250 m |

As already noted in Section 3.2.4 the DFN-model of the Laxemar subarea is uncertain, but the uncertainty is not quantified. However, since the uncertainties both relate to fracture intensity and fracture size they are likely to have a profound impact on the calculated fraction of *canisters* being intersected by discriminating fractures. As shown by /Hedin 2005/ the fraction is essentially proportional to the fracture intensity, if all other parameters are kept constant. However, matching a DFN-model to site data generally requires adjusting also the size intensity parameters ($k_r$ and $r_0$), which means that no meaningful estimates of the impact of the uncertainty can be made without first quantifying the uncertainty of the DFN-model. Such quantification lies outside the scope of this PSE and of the safety assessment SR-Can, but will be undertaken for the SR-Site assessment.

### *Impact on degree of utilisation*

It is foreseen that the impact of potential post-glacial faulting would be mitigated by implementing a design rule where deposition holes with fractures in excess of the critical radius are not used. However, in order to ensure a high probability of identifying the deposition holes intersected by fractures (or minor deformation zones) larger than the critical radius, it is likely that any applied procedure for discarding deposition holes would imply that some holes intersected by shorter fractures would also be ("unnecessarily") discarded. These issues are also studied in the separate SKB project mentioned previously.

One of the objectives with the design phase D1 is to determine whether the final repository can be accommodated within the studied site. The procedure is described in the design premises /SKB 2004c/. Deposition holes intersected by fractures with radii in the interval 50–600 m are to be discarded. Fractures larger than 600 m are assumed to have been avoided already in the layout.

Applying this rule results in around 16 percent discarded canister positions, using the method described by /Hedin 2005/, Laxemar rock domain A DFN data and a minimum excluded fracture of 50 m radius. This value refers to positions in the 100 to 200 m band from the deformation zones requiring a respect distance. For positions farther away, where only fractures larger than 100 m radius need to be avoided, the corresponding figure is 7.4 percent.

The percentage of discarded canister positions, calculated in this way, is higher than the 2.7 (or 0.5) percent resulting from the safety assessment calculation. The difference is due to the considerably smaller volume in the safety assessment calculation (the canister volume rather than that of the deposition hole), and also to the fact that the outermost part of a discriminating fracture is excluded from that calculation, since the movement in that part of the fracture is assumed too small to damage the canister, see further /Hedin 2005/. Also, the lower limits of fracture sizes (50 and 100 m) in the calculation of degree-of-utilisation are different from the corresponding limits (75 and 150 m) in the safety assessment calculation.

**Table 3-6. Summary of calculations of Fraction of canisters being intersected by discriminating fractures and deposition holes intersected by fractures. All results concern the DFN-model for rock domain RSMA.**

| Fraction of canisters being intersected by discriminating fractures, ε, of radius larger than 75 m | Fraction of canisters being intersected by discriminating fractures, ε, of radius larger than 150 m | Deposition holes intersected by fractures with radii in the interval 50–600 m | Deposition holes intersected by fractures with radii in the interval 100–600 m |
|---|---|---|---|
| 2.7% | 0.5% | 16% | 7.4% |

This difference is due to a recent update of the prerequisites for the safety assessment calculations based on additional knowledge regarding secondary movements of fractures, see “additional considerations” in Section 3.2.1. The prerequisites for the calculation of degree-of-utilisation will need to be updated accordingly.

### 3.2.7 Safety implications

The previous sections show that the Laxemar subarea meets all geological requirements and preferences, although there are considerable uncertainties in the statistical fracture model (the DFN-model):

- It is well established that the subarea does not have any ore potential or other potentially valuable resources. The rock type distribution represents typical crystalline basement rock and the remaining uncertainties are of little concern for safety.
- It is clearly possible to locate a sufficiently large repository within the Laxemar subarea while meeting the required respect distances to the deformation zones and assuming a low degree of utilisation. There is considerable reserve space. However, it also noted that there is considerable uncertainty in the character and geometry of the deformation zones in the area, which means that the current layout of design step D1 would likely need to be substantially altered when a less uncertain description is available.
- Even allowing for uncertainties in the DFN-models applied, the calculated proportion of potential canister positions being intersected by discriminating fractures of radius larger than 75 m is in the order of a few percent. This proportion of potentially unsuitable deposition holes is much less than what is assumed in the layout when assessing the degree of utilisation.
- For the Safety Assessment, there is also a need to consider the probability of identifying the deposition holes intersected by large fractures. Initial such assessments, focusing on finding how good such practical identification needs to be in order to constrain unjustified conservatism, will be made in SR-Can. Improved estimates should follow as a part of the detailed investigation programme, see below.

Even though the geological requirements and preferences are already considered to be met, further reduction in the uncertainties in the structural and DFN geological model would enhance the safety case and would also allow for a more efficient design:

- Reducing the uncertainty on the deformation zone geometry inside the Laxemar subarea would be helpful to confirm the size and to better define the location of the suitable deposition volumes. The additional data to be collected and the subsequent evaluation, as suggested in SDM L1.2 are considered appropriate for this purpose.

- There is substantial and, as yet, un-quantified uncertainty in the DFN-model. Efforts need to be spent on quantifying and reducing these uncertainties. More data are needed from the potential repository volume as further discussed in Chapters 12 and 13 of SDM L1.2, but there is a limit to the degree to which these uncertainties can be reduced using only information from surface-based investigations.
- Efforts need also be spent on improving the DFN-modelling. There are assumptions made in current models that could be challenged and there seems to be room for making better use of the borehole information. It is especially important to provide robust estimates of the intensity of large fractures and features, e.g. $P_{32}$ and the $k_r$ parameter in the power-law distribution, and further efforts should be spent on providing good support for the possible ranges of these parameters. In contrast, details of the orientation distribution of fractures are of much less importance.
- Further reduction of the uncertainties, if needed, would probably only be possible from studies underground, during the detailed investigation phase. Presently, the overall strategies for detailed investigations during the construction phase are under development. Whatever strategies that are defined now, these will have to be adapted to experience gained during tunnelling, both in the aspect of identifying any site specific signature of long fractures/small deformation zones, including hydraulic indications of such zones as well as to incorporating this into the training of geologists for the required field work and detailed modelling.

Finally, it is noted that the design rules for discarding canister positions due to potential intersections with fractures or deformation zones larger than the critical size seem to be too restrictive, in the sense that currently estimated degree of utilisation is less than the percentage of potential canister positions really being intersected by a discriminating feature. The issue of concern is to devise a practical method of identifying these positions with a very high probability, without overly reject positions that in fact are not intersected by a discriminating feature. For this reason, SKB has now started a project aiming at practical methods of estimating the probability of identifying the deposition holes intersected by large fractures or deformation zones. This assessment should also produce more realistic estimates of the degree-of-utilisation.

## 3.3 Rock mechanics

Many of the requirements and preferences relating to rock mechanics concern implications for Repository Engineering. However, there are also important safety considerations. Especially, it is important to evaluate the mechanical stability of the deposition holes.

### 3.3.1 Criteria and other safety considerations

#### *Previously set criteria*

The suitability criteria, as set out by SKB in /Andersson et al. 2000/, directly related to the rock mechanics of the site, concern initial rock stress and rock mechanics properties of the intact rock, the fractures and the rock mass.

In order to ensure safe working conditions and that the deposition hole geometry will be within given tolerances, it is *required* that extensive spalling or other extensive overbreak may not occur within a large portion of the deposition area. The fulfilment of this requirement is to be verified by means of a site-specific analysis. There was also a stated *preference* for normal in situ stress levels (maximum principal stress component considerably lower than 70 MPa), and intact rock strength and deformation properties that are typical of Swedish bedrock. However, these old preferences are now less meaningful since rock mechanics analyses checking the risk of spalling are indeed carried out allowing checking for the spalling criterion directly.

It is further stated that the calculated stress situation in the rock nearest the tunnels and the resultant rock stability during and after the construction phase is used mainly to adapt repository depth and layout. If the repository cannot be reasonably configured in such a way that extensive and general stability problems can be avoided, the site is unsuitable and should be abandoned. Extensive problems with "core disking" should give rise to the suspicion that problems may be encountered with spalling during tunnelling. There should also be special attention given to rock mechanics issues if the strength of the rocks deviates from typical values of Swedish bedrock.

There are no requirements on the rock mechanics properties of fractures and fracture zones or of the rock mass. It is noted that these properties are used by Repository Engineering for developing the layout and for constructability forecasting. Good constructability is of course advantageous.

There is no requirement on the coefficient of thermal expansion, but the discussion in /Andersson et al. 2000/ considered whether an inhomogeneous expansion could impair the stability of deposition holes. Therefore, there was a *preference* for typical values for Swedish bedrock and for limited inhomogeneity and anisotropy.

#### *Additional considerations*

There are no additional considerations. The possibility and consequences of spalling in deposition holes due to the thermal load are to be explored within SR-Can, see also Chapter 10 of the SR-Can interim report /SKB 2004a/. However, ongoing analyses suggest that inhomogeneity in thermal expansion would not be an issue. Rather the key factors are the in situ stress and the intact rock strength. If there is a risk of thermally induced spalling, it would occur in the rock type with the lowest strength.

### 3.3.2 Stress and rock mechanics properties

#### *Stress*

According to SDM L1.2, Chapter 6, both data and stress modelling results suggest that the Laxemar subarea could be divided into two different stress domains (I and II), where Stress Domain II has lower stresses. It is recognised that the essentially northeast trending deformation zones on either side of the Simpevarp peninsula-Hålö-Ävrö (i.e. zones ZSMNE012A and ZSMNE024A) can be interpreted to form a wedge-shaped body of rock that may represent a different stress regime from that prevailing at Äspö. Similarly, the rock volume above zones ZSMEW007 and ZSMEW002 forms a wedge in the Laxemar subarea. While these two domain II volumes are physically separated, the reason for lower stress are similar in both volumes. When the measured stress data are sorted into two different groups representing these assumed geographical domains it is noted that the spread within each group is significantly reduced compared with the combined spread of the two groups of data in combination, see Figure 3-8.

The hypothesis of a structure-controlled explanation for the noted stress variation in the local scale model volume was evaluated using a numerical model, see /Hakami and Min 2006/. The applied stress boundary conditions, simulating tectonic compression in the direction NW-SE, are assumed to have prevailed during the latest evolutionary period.

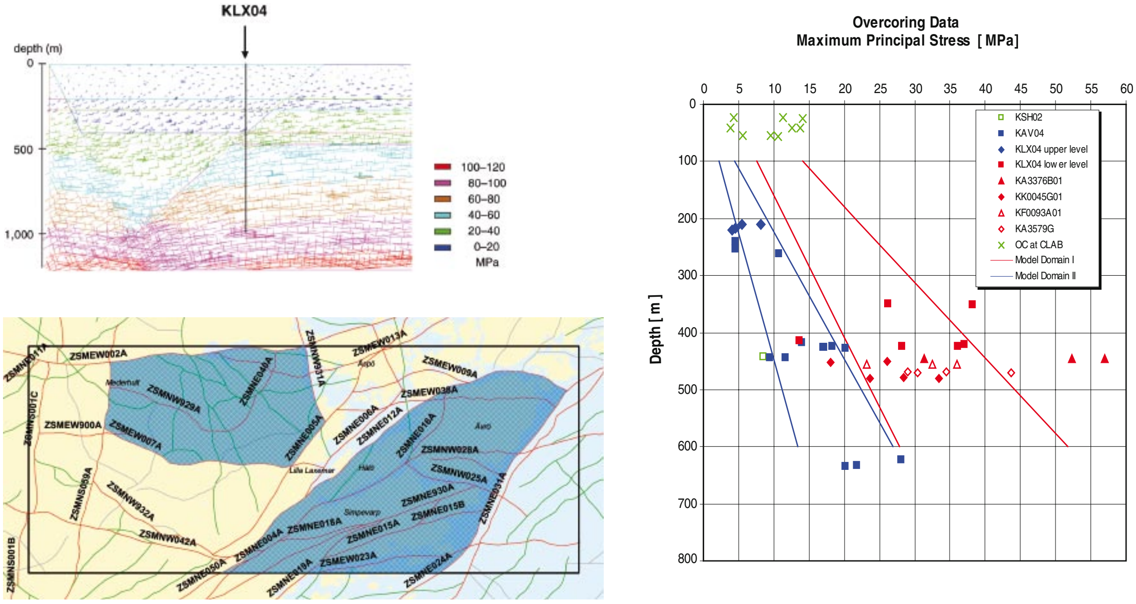

***Figure 3-8.** Both data and stress modelling results suggest that the Laxemar subarea could be divided into two different Stress Domains (I and II). Stress domain II, the domain with lower stresses is indicated in blue. (Based on figures 6-5, 6-16 and 6-19 in SDM L1.2).*

From the modelling results, it can be seen, as expected, that wedge-shaped rock masses surrounded by deformation zones with reduced strength properties, are not able to sustain high horizontal stresses, and the stress consequently becomes lower inside the wedge and higher in areas outside, as illustrated in Figure 3-8. The results, although subject to uncertainty, thus support a conceptual stress model describing the stress state in the modelled area as being made up of two different stress domains.

Table 3-7 shows estimated stress levels for Stress Domain I and Table 3-8 shows estimated stress levels for Stress Domain II. The tables also show estimates of uncertainty and of spatial variability. The reasons for uncertainty in the stress model are several. Firstly, the accuracy of the measurements themselves is limited. Secondly, the amount of data is not large, from a statistical viewpoint, and the fitted linear stress model functions have an inherent uncertainty due to this fact. Thirdly, the assumptions made regarding the stress domains and the need to extrapolate the available measurement results over large volumes also contribute to the uncertainty. The value selected for the total uncertainty thus encompasses different contributions and is based on an expert judgement for each contribution.

**Table 3-7. Model of in situ stress magnitudes in the Laxemar 1.2 Stress Domain I (Table 6-9 of SDM L1.2).**

| Parameter | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ |
|---|---|---|---|
| Mean stress magnitude (MPa), z = depth below ground surface (m) | $0.058 \cdot z+5$ | $0.027 \cdot z$ | $0.014 \cdot z + 3$ |
| Uncertainty, 100–600 m | ± 30% | ± 30% | ± 30% |
| Spatial variation in rock domains | ± 20% | ± 20% | ± 20% |
| Spatial variation in or close to deformation zones | ± 50% | ± 50% | ± 50% |

**Table 3-8. Model of in situ stress magnitudes in the Laxemar 1.2 Stress Domain II (Table 6-11 of SDM L1.2).**

| Parameter | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ |
|---|---|---|---|
| Mean stress magnitude (MPa), z = depth below ground surface | 0.032·z | 0.027z | 0.01·z |
| Uncertainty, 100–600 m | ± 30% | ± 30% | ± 30% |
| Spatial variation in rock domains | ± 25% | ± 25% | ± 25% |
| Spatial variation in or close to deformation zones | ± 50% | ± 50% | ± 50% |

### *Rock Mechanics Properties of Intact Rock*

The rock mechanics properties of the intact rock, together with the rock stress, affect the risk of spalling, both during construction and as a result of the thermal load. According to SDM L1.2, Chapter 6, laboratory data from the site investigation program are available for the three most abundant rock types. The values were basically taken "as is" from the test results but with some adjustments. The spread (the standard deviation) in the normal distribution was not always taken directly as the spread in the test results, because the number of tests was not sufficient. In such cases the spread was judged also based on experience from the spread for other rock types. The model values were also all selected as rounded off numbers, so as not to give a false impression of certainty in the parameter value assignments.

It is reasonable to believe also that the crack initiation stress should be higher in a sample where the maximum uniaxial stress at failure is high. In such a case, an uncorrelated distribution for each parameter would not be an appropriate description. Therefore, the correlation between these two parameters was studied and was found to be confirmed for all rock types. The crack initiation stress parameter is modelled as a function of the Unixial Compressive Strength (UCS). The crack initiation stress is about 50% of the UCS for Ävrö granite and 47% for the other rock types.

The assignment of mechanical properties to three intact rock types is provided in Table 3-9. The rock type proportions in the defined rock domains are described in the Geology Sections of SDM L1.2, and outlined in Section 3.2.2 above. In particular, the UCS depends on rock type, with the lowest strength in quartz-monzonite to monzodiorite, i.e. a rock type found in the RSMD domain of the Laxemar subarea.

To describe the uncertainty in the estimations, an estimated span is given within which the real mean value is considered to lie. This is regarded as an improvement compared with previous model versions. The uncertainty span was selected based on the statistical analysis of the data sample (the 95% confidence values around the mean). When the number of samples is large the uncertainty span naturally decreases. However, when selecting the uncertainty value the accuracy in the determination of the test parameter was also considered. The uncertainty description value was further, for simplicity, selected as a single symmetrical value and this value finally chosen by expert judgement. The variation between samples is largely due to variability in mineralogy between samples. Especially, the total spread in the uniaxial compressive strength expected for the Ävrö granite is quite large, 150–240 MPa, probably reflecting the large variation in Ävrö granite mineralogy.

**Table 3-9. Estimated rock mechanics properties for intact rock (i.e. small pieces of rock without any macroscopic fractures) of the most abundant rock types. All parameters are described as truncated normal distribution functions. (From Table 6-5 of SDM L1.2).**

| **Parameter for intact rock (drill core scale)** | **Granite to Quartz-monzodiorite (Ävrö granite)**<br>**Mean/standard dev.**<br>**Min–Max (trunc.)**<br>***Uncertainty in the mean*** | **Quartz-monzonite to monzodiorite**<br>**Mean/standard dev.**<br>**Min–Max (trunc.)**<br>***Uncertainty in the mean*** | **Finegrained dioritoid**<br>**Mean/standard dev.**<br>**Min–Max (trunc.)**<br>***Uncertainty in the mean*** |
|---|---|---|---|
| Uniaxial compressive strength, UCS* | 195 MPa / 20 MPa<br>150–240 MPa<br>± 5 MPa | 165 MPa / 30 MPa<br>110–200 MPa<br>± 8 MPa | 210 MPa / 50 MPa<br>120–265 MPa<br>± 10 MPa |
| Crack initiation stress, σci | 0.50 x UCS<br>± 7 MPa | 0.47 x UCS<br>± 9 MPa | 0.47 x UCS<br>± 10 MPa |
| Young's modulus, E | 70 GPa / 5 GPa<br>60–90 GPa<br>± 2 GPa | 80 GPa / 10 GPa<br>70–90 GPa<br>± 3 Gpa | 85 GPa / 10 GPa<br>70–110 GPa<br>± 3 GPa |
| Poisson's ratio, υ | 0.20 / 0.03<br>0.15–0.26<br>± 0.01 | 0.27 / 0.05<br>0.18–0.33<br>± 0.01 | 0.26 / 0.03<br>0.19–0.31<br>± 0.01 |
| Tensile strength, T | 13 MPa / 1.5 MPa<br>9–17 MPa<br>± 1 MPa | 17 MPa / 4 MPa<br>12–24 MPa<br>± 1 MPa | 20 MPa / 2 MPa<br>14–24 MPa<br>± 1 MPa |
| Mohr-Coulomb Friction angle, φ | 56° / 2°<br>53°–57°<br>± 1° | 60° / 3°<br>57°–62°<br>± 1° | 55° / 6°<br>35°–60°<br>± 1° |
| Mohr-Coulomb Cohesion, c* | 27 MPa / 2.7 MPa<br>23–32 MPa<br>± 2 MPa | 22 MPa / 3.2 MPa<br>14–29 MPa<br>± 2 MPa | 32.5 MPa / 5.4 MPa<br>20–40 MPa<br>± 2 MPa |

* The UCS should not be used as input to the Mohr-Coulomb model

As noted in Chapter 12 of SDM L1.2 the rock mechanics properties for intact rock of rock type Quartz monzodiorite and the Ävrö granite in the southern part of the Laxemar subarea are possibly biased, since only laboratory tests from the Simpevarp subarea and northern Laxemar are available. The Ävrö granite in southern Laxemar is expected to have lower quartz content than the available samples of Ävrö granite, and the quartz content may affect the mechanical properties. This uncertainty has not yet been quantified in L1.2, but will be in future versions.

### *Rock Mechanics Properties of the Rock Mass*

The rock mechanics model also covers properties of the rock mass. These properties are important for Rock Engineering, but have few direct safety implications. Therefore, these properties are not summarised here.

### Coefficient of thermal expansion

As further explained in Section 7.2.7 of SDM L1.2, the coefficient of thermal expansion has been measured on borehole samples from the Simpevarp and Laxemar subareas /Åkesson 2004a–f/. The mean value of measured thermal expansion varies for the different rock types between $6.9 \cdot 10^{-6}$ and $8.2 \cdot 10^{-6}$ m/(m·K). The standard deviation in the data is less than $2 \cdot 10^{-6}$.

## 3.3.3 Mechanical stability during construction and operation

The layout D1 design work for the Laxemar subarea /SKB 2006b/ assessed the risk of spalling of deposition tunnels and deposition holes, using the stress and intact rock properties discussed in Section 3.3.2. The analysis is based on the assessment by /Martin 2005/).

/Martin 2005/ draws the following conclusions:

- In Stress Domain II spalling in the deposition holes will not be encountered regardless of repository depth. In Stress Domain I the risk for spalling in the deposition holes increases below a repository depth of 450 m. At 550 m depth the probability of spalling is approximately 20% while at a repository depth of 650 m the probability for spalling increases to approximately 60%, but the corresponding depth of spalling is limited, see Figure 3-9.
- There is no probability of spalling in the deposition tunnels in stress Domain II at any depth or orientation. However, in Stress Domain I, the deposition tunnels oriented perpendicular to the maximum horizontal stress will likely encounter minor spalling below 500 m depth.

/Martin 2005/ calculated the probability of spalling using the @Risk Monte Carlo simulations with the uncertainty in stress and mechanics properties as input. For these simulations no correlation between stress and crack initiation stress was assumed, i.e., the highest stress can be associated with the lowest strength. In reality, this may not be the case as the highest in situ stresses are often found in the most competent rock mass and the lowest stresses in highly fractured rock masses, i.e. assuming no correlation may overestimate the probability of spalling. The output for the spalling factor of safety provides the mean factor of safety as well as the probability of the factor of safety being less than 1.

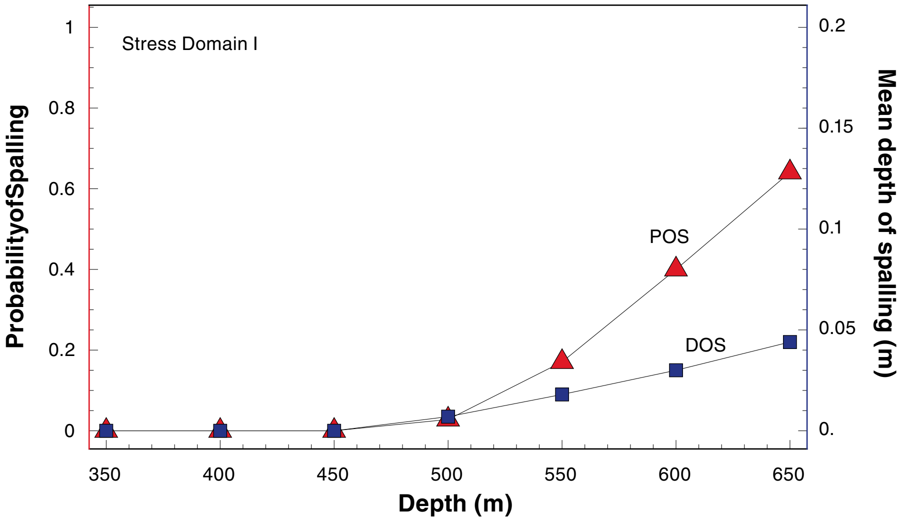

*Figure 3-9. Probability of spalling (POS) for deposition holes in Stress Domain I of Laxemar and the corresponding depth of spalling (DOS). (Figure 6-3 in /Martin 2005/).*

If there is 10% probability that the spalling factor of safety is less than 1, this implies that for a 100 m long tunnel, there is the potential that 10 m of the tunnel length will experience spalling. If there is 0% probability of spalling there is no depth of spalling. However, once the probability of spalling is greater than zero, a depth of spalling is determined. For the depth of spalling, only the mean depth of spalling was used for assessing the severity of the hazard.

The layout D1 design work for the Laxemar area /SKB 2006b/ concludes that even if a deposition tunnel oriented parallel with the main principal stress orientation would minimize the risk of spalling in the tunnels, the overall risk is judged too small to impact the design. Tunnel orientation is not selected based on stress orientation.

Even if there is a non-zero probability of spalling in deposition holes at the –500 m level, the volume of spalled rock is limited. Using the depth of spalling as predicited by /Martin 2005/, the Laxemar design work /SKB 2006b/ calculated the volume of spalled rock and concluded that accepting a spalled volume of 0.15 $m^3$ implies that spalling to a depth of ca 0.025 m would not lead to rejection of the deposition hole. Therefore, there would not be a need to reject any deposition hole using this criterion.

Finally, it must be understood that the spalling analysis of /Martin 2005/ assumes a uniform stress distribution along the deposition hole. In reality the deposition holes are 8 m long and connected to a deposition tunnel. Hence, the stress magnitudes along the deposition hole will not be uniform. Three-dimensional stress analysis using the tunnel geometry and deposition hole spacing should be carried out for those cases where the probability of spalling is significant. Such analyses are conducted within SR-Can, using the 3DEC code.

### 3.3.4 Safety implications

The above sections show that the Laxemar subarea meets all the rock mechanics requirements.

- The rock mechanics properties of the intact rock lie within ranges typical of Fennoscandian crystalline rock, although the uniaxial compressive strength is comparatively low.
- Also the stress levels are typical of the Fennoscandian crystalline rock. In Stress Domain II, the stresses are generally low, whereas more elevated stress levels are found in Stress Domain I.
- In Stress Domain II, spalling in the deposition holes will not be encountered regardless of repository depth. In Stress Domain I the risk of spalling in the deposition holes increases below a repository depth of 450 m. At 550 m depth the probability of spalling is approximately 20% while at a repository depth of 650 m the probability of spalling increases to approximately 60%, but the corresponding depth of spalling is limited. This means that there will be some likelihood of spalling in deposition holes at 500 m, even if the volume change may be so small that few, if any, deposition holes would need to be discarded for this reason.
- There is no probability of spalling in the deposition tunnels in stress Domain II at any depth or orientation. However, in Stress Domain I, deposition tunnels oriented perpendicular to the maximum horizontal stress will likely encounter minor spalling below 500 m depth.

- Considering the high stress levels in relation to the uniaxial compressive strength UCS in Stress Domain I, the possibility and consequences of spalling in deposition holes due to the thermal load cannot be excluded. This is an issue to be further explored within SR-Can.
- There is only moderate variation in the coefficient of thermal expansion.

It should be noted that spalling in deposition holes prior to deposition has no direct safety implications. Once spalling has occurred the resulting shape of the excavation is very stable. If the spalling is excessive the deposition hole would be rejected, otherwise the additional volume would not be a problem or could easily be handled by adding additional buffer material to the hole. However, if spalling occurs after deposition, i.e. due to the thermal load, abandoning the hole would not be a practical option. Therefore SR-Can explores the consequences of buffer stability and radionuclide migration in case such spalling would occur.

Considering the uncertain stress levels, in combination with the comparatively low Uniaxial Compressive Strength of the intact rock, further reductions in the uncertainties in stress and rock mechanics properties are needed. There is a need to obtain representative data from all important rock types in the potential repository volume. The additional data suggested in Chapter 13 of SDM L1.2 are considered appropriate to fill these needs. Also, the issue of spalling due to the thermal load requires additional analyses, as already envisaged for SR-Can. This may also lead to additional data demands.

## 3.4 Thermal analyses

The thermal conductivity of the rock mass affects the thermal evolution of the canister and the bentonite buffer. This is of importance for safety, since elevated temperatures in the buffer may affect the properties of this important barrier. However, the temperature could generally be controlled by an appropriate design.

### 3.4.1 Criteria and other safety considerations

#### *Previously set criteria*

The suitability criteria, as set out by SKB in /Andersson et al. 2000/, directly related to the thermal properties of the site apply to the thermal conductivity and the initial temperature profile. The criteria are based on the *requirement* that the temperature on the canister surface and in the buffer must not exceed 100°C, in order to ensure predictable canister corrosion and buffer stability. However, these requirements have now revised, see next section.

No requirements are set on the rock thermal conductivity, but a *preference* for thermal conductivity, which influences repository layout and repository size, larger than 2.5 W/(m·K) was given. It was also noted that, during the site investigation, detailed knowledge of rock types and their thermal conductivity is used to adapt the repository layout.

Also, there are no requirements on initial temperature, although areas with potential for geothermal energy extraction (very high geothermal gradient) should be avoided. A *preference* was set that the initial temperature at repository depth should be less than 25°C.

### *Additional considerations*

Based on new data and knowledge, the thermal requirements on the final repository have been revised.

As will be further discussed in the Fuel and Canister Process report for SR Can /SKB 2006c/ data from the LOT experiment /Karnland et al. 2000/ imply that salt deposits on the canister surface will occur both above and below the boiling point. However, to induce corrosion at the pH conditions expected at the bentonite/canister interface, an oxidant (other than water) would have to be present even at high chloride concentrations /King et al. 2001/. The corrosion rate is, therefore, expected to be controlled by the availability of dissolved oxygen in the water, rather than the possible presence of chloride deposits on the canister surface. It is thus concluded that exposures to temperatures over 100°C will not have a negative effect on the corrosion behaviour of the copper canister.

Requirements on the buffer are still valid. The buffer temperature should not exceed ca 100°C in order to limit adverse chemical alterations, see the Buffer and Backfill Process Report for SR-Can /SKB 2006d/. This means that the repository must be designed such that the buffer temperature does not exceed a certain value, currently assessed to be around 100°C, taking all uncertainties relevant to the temperature determination into account.

## 3.4.2 Thermal properties and initial temperature

### *Thermal conductivity and heat capacity*

As further explained in Chapter 7 of SDM L1.2, the thermal conductivity at canister scale is modelled using various approaches. Table 3-10 lists resulting distributions of thermal conductivity for the various rock domains in the potential repository volume in the Laxemar subarea, i.e. a subset of the domains listed in Section 3.2.2. The ranges essentially represent spatial variability between different canister positions, although there is also an uncertainty contribution. It should also be noted that the thermal conductivity decreases slightly at higher temperatures, 1–5% per 100°C temperature increase.

Within the rock domains the thermal conductivities cannot be shown to be normal distributed. This is most likely due to the fact that the rock domains consist of a mix of rock types of different thermal properties. Therefore, estimates of lower tail 0.5 and 2.5 percentiles based on the listed standard deviations cannot be calculated using parametric methods. To estimate lower tail percentiles for the listed standard deviations, a correction is made as is described in /Sundberg et al. 2006/.

The resulting values are suggested to be reasonable approximations of the respective percentiles for the 0.8 m scale, see Table 3-10. It should be mentioned that uncertainties associated with the estimation of percentiles become larger at the extreme ends of the distributions. Because no scaling up has been performed for domains RSME and RSMM, the lower tail percentiles estimated from realisations based on Monte Carlo simulation, are conservatively low for larger scales. By taking into account the effect of upscaling observed in the other domains, which on average is about 0.2 W/(m·K) for the 0.8 m scale, corrected lower 0.5 and 2.5 percentiles[4] can be approximated for these domains, see Table 3-10. Obviously, these approximations are uncertain.

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[4] The selection of percentiles is somewhat arbitrary, but illustrates that the lower end of thermal conductivity values are higher then what would result from assuming a normal distribution with the mean and standard deviation found.

**Table 3-10. Recommended mean, standard deviation and lower tail percentiles of thermal conductivity (W/(m·K)) per domain in the potential repository volume at 0.8 m scale. For RSME and RSMM, a rough correction has been applied to percentiles estimated from Monte Carlo simulated distributions, which are based on a < 0.1 m scale. The table is valid at 20°C. The thermal conductivity decreases slightly at higher temperatures, 1–5% per 100°C temperature increase. (Table 7-17 of SDM L1.2).**

| Domain | Mean | St. dev | 0.5 percentile | 2.5 percentile | 97.5 percentile |
|---|---|---|---|---|---|
| RSMA | 2.82 | 0.29 | 2.20 | 2.32 | 3.39 |
| RSMBA | 2.87 | 0.29 | 2.24 | 2.37 | 3.43 |
| RSMD | 2.70 | 0.17 | 2.32 | 2.44 | 3.19 |
| RSME | 2.45 |  | 2.0 | 2.2 | 3.0 |
| RSMM | 2.58 |  | 2.2 | 2.3 | 2.8 |

Results of modelling of heat capacity within the rock domains, presented in Table 7-15 of SDM L1.2 for four domains, indicate a small range (2.23–2.29 MJ/(m·K) at 20°C) in mean heat capacity and a low standard deviation (0.13 MJ/(m·K)).The heat capacity increases by approximately 25% per 100°C for the dominating rock types.

As also noted in L1.2, the modelled thermal properties are uncertain due to potentially poor representativity of the samples taken for laboratory testing, uncertainty in the density logging method used to estimate thermal conductivity along boreholes and uncertainties in the scaling. There are few data from rock domains ME and MM and no representative boreholes. Altered rock ('red-staining') has not been analysed, but it is thought that this altered rock has higher thermal conductivities than unaltered rock. The thermal conductivity of Ävrö granite derived from density logging is uncertain although the validity in using density to calculate thermal conductivity in rock type Ävrö granite (501044) has been demonstrated. There are only few data confirming the relation for samples with low thermal conductivities. There are uncertainties in the large-scale variations within domains with medium or low presence of Ävrö granite since only a small number of boreholes have been used to characterise these domains and since the three-dimensional geometry of most of the rock domains is uncertain. The uncertainty and spatial variability are nevertheless estimated, see e.g. Table 3-10, but more representative data would improve the confidence in these estimates.

### *Initial temperature*

As further explained in Chapter 7 of SDM L1.2 the in situ temperature and gradient profiles have been measured by fluid temperature logging in five boreholes. The mean of all temperature loggings over specific depth intervals provided as mean values of the in situ temperature at 400, 500 and 600 m depth are estimated to be 12.1, 13.8 and 15.5°C, respectively, see Table 7-10 of SDM L1.2. The mean temperature seems to vary almost linearly with depth.

There are potential errors in the loggings, demonstrated by a difference in temperature for the same borehole logged on different occasions. This is probably due to measurement errors, disturbance from the drilling and water movements along the boreholes. Although this difference in temperature is relatively small for a specified depth, the influence on the design of a repository may be important. The uncertainty is quantified as a range. For more details, see /Sundberg et al. 2006/.

### 3.4.3 Thermal evolution of canister surface, buffer and near field rock for present climate conditions

#### *Temperature calculations performed by Rock Engineering*

In the layout work /SKB 2006b/, the thermal properties and the initial temperature of the different rock domains are used to calculate the necessary distance between deposition holes, in order to ensure that the temperature criterion for the buffer is met. Also *the abandoned criterion on peak canister* temperature, requiring that it should not exceed 100°C *is applied*. The design rule is provided in the Underground Design Premises document /SKB 2004c/. The rule is based on the analyses performed by /Hökmark and Fälth 2003/.

Table 3-11 shows the resulting minimum spacing, based on the mean thermal conductivity of the rock domains potentially present in the repository volume for different depths. This minimum canister spacing is based on 40 m separation between deposition tunnels, using mean temperature and mean heat capacity as given by the SDM L1.2. In order to account for the spatial variability of the thermal conductivity, the design formula uses a safety margin of 10°C. Another 10°C safety margin is introduced to account for the effects of the potential gap between canister and buffer and the gap between buffer and rock. This means that the calculated peak canister temperature, before added margins for variability and gaps, with the selected canister spacing and for the mean thermal conductivity is about 80°C.

As can be seen from the table, the analysis suggests canister spacing at 500 m depth in the range 7.0 m to 8.1 m, depending on rock domain. However, it is also noted that the spatial variability of thermal conductivity may be larger than could be handled by the margin introduced in the formula by /Hökmark and Fälth 2003/. For example, considering the 0.5-percentile values of thermal conductivities shown in Table 3-10 would require a minimum separation distance of 8.5 m in RSMA and 8.7 m in RSMM at the 500 m depth level.

The suggested layout at 500 m depth considers a mean canister separation distance of 7.4 m. As can be seen from Table 3-11 this would be sufficient for the mean thermal conductivity of rock domains RSMA and RSMBA, but would be too low in rock domains RSMD and RSMM. If these domains and the spatial variability down to the lower 5-percentile values are taken into account the needed repository area would increase by about 20 percent /SKB 2006b/. This is a substantial increase, but more than adequate reserve areas exists within the Laxemar subarea. Furthermore, the relaxed temperature criterion introduced since the Rock Engineering work, would most likely imply that these extra canister separations are unnecessary.

**Table 3-11. Minimum required distance between deposition holes for different depths for different rock domains, based on the mean value of thermal conductivity. (From /SKB 2006b/).**

| Repository depth (m) | Distance (m) | | | |
|---|---|---|---|---|
| | RSMA | RSMBA | RSMD | RSMM |
| 400 | 6.9 m | 6.7 m | 7.2 m | 7.6 m |
| 500 | 7.2 m | 7.0 m | 7.6 m | 8.1 m |
| 600 | 7.6 m | 7.4 m | 8.1 m | 8.6 m |
| 700 | 8.0 m | 7.8 m | 8.5 m | 9.2 m |

### *Supplementary temperature calculations*

The safety margin used in the design work should account for most of the spatial variability in the thermal conductivity. However, in order to assess whether there is any likelihood of the buffer in individual deposition holes reaching temperatures above 100°C, some additional calculations based on the thermal properties of the Laxemar subarea are presented below. The analysis is otherwise based on the same premises as described in the SR-Can Interim report /SKB 2004a/.

The peak temperatures as a function of time in the fuel, the cast iron insert, the copper canister, the buffer and the host rock were calculated using an analytic model /Hedin 2004/. The model has been verified against numerical results. It is based on analytical solutions describing the canisters as a set of point sources in the host rock and steady-state heat conduction expressions are used for heat conduction in the buffer. Furthermore, heat transfer due to combined radiation and conduction in the gaps between canister and buffer and in the canister interior is calculated analytically. That is, the analysis does not apply the added margins used in the design work, it models the temperature drop over the canister/buffer and buffer/rock interfaces explicitly.

Similar treatments are presented for the host rock and buffer in /Hökmark and Fälth 2003/. Benchmarking against the results of /Hökmark and Fälth 2003/ and against numerical finite element calculations for buffer and rock yields discrepancies of peak canister temperature of less than one degree /Hedin 2004/.

Primary rock thermal data for the calculation were obtained from the SDM L1.2, summarised in Section 3.4.2 above. In order not to overestimate the heat conduction, the thermal conductivity values were assessed for 80°C. The resulting recommended values of thermal properties for rock domains RSMA and RSMM (examples of rock domains where the repository would be located) are shown in Table 3-12. SDM L1.2 notes that the thermal conductivities within a rock domain cannot be shown to be normal distributed. For SR-Can, it is instead proposed to use a truncated normal distribution with the lowest value set to the 0.5 percentile. Full documentation of this data evaluation will appear in the SR-Can data report, due in 2006.

Table 3-13 lists additional data needed for the thermal calculations. For example, different canister separation distances, consistent with the details of the design /SKB 2006b/, are used in rock domain RSMA and RSMM respectively.

**Table 3-12. Thermal properties to be used in peak temperature calculations in SR-Can.**

| Domain | Temperature at repository depth °C | Thermal conductivity at 80°C [W/(m·K)] | S. dev. in thermal conductivity [W/(m·K)] | Suggested lowest value in thermal conductivity [W/(m·K)] | Heat capacity [MJ/(m³·K)] |
|---|---|---|---|---|---|
| RSMA | 13.8 (at 500 m depth) | 2.77 | 0.29 | 2.20 | 2.24 |
| RSMBA | 13.8 (at 500 m depth) | 2.82 | 0.29 | 2.24 | 2.23 |
| RSMD | 13.8 (at 500 m depth) | 2.65 | 0.17 | 2.32 | 2.29 |
| RSME | 13.8 (at 500 m depth) | 2.40 | 0.2 | 2.0 | 2.25 |
| RSMM | 13.8 (at 500 m depth) | 2.53 | 0.2 | 2.2 | 2.25 |

**Table 3-13. Thermal sub-model data for the central case presented in Figure 3-10. Site-specific data are taken from SMD L1.2. The void space inside the canister is assumed to be filled with air. The rock is assumed homogeneous. All other data required for the calculation are given in Table 7-3 and Figure 7-2 of /SKB 2004a/.**

| | |
|---|---|
| Repository depth | 500 m |
| Canister spacing RSMA | 7.2 m |
| Canister spacing RSMM | 8.1 m |
| Buffer thermal conductivity | 1.1 W/(m·K) |
| Gap buffer/rock | 0.03 m |
| Gap canister/buffer | 0.005 m |

Figure 3-10 shows the results of the complementary thermal calculation of the thermal evolution at a number of points located on a radius extending horizontally from the canister mid-point along the deposition tunnel for rock domain RSMA. The results for domain RSMM are almost identical. The peak canister outer surface temperature at canister mid-height is 93°C for both Rock Domain RSMA and RSMM, for the input data as listed in Table 3-13, and decreases towards the end of the canister. The mean value of rock thermal conductivity was used. When the peak canister temperature occurs, the temperature drop across the 5 mm gap between canister and buffer is around 11°C meaning that the buffer inner temperature is 82°C. The corresponding drop across the 30 mm gap between buffer and rock wall is around 4.5°C.

It is noted that the theoretical calculation of temperature drops across these gaps assumes idealised geometries and other properties related to the absorption/reflection of heat radiation. Back-calculation of experimental data obtained from SKB's prototype repository at the Äspö laboratory suggests that the temperature drop between canister and buffer may correspond to an effective copper surface heat emissivity of 0.3, rather than the laboratory-determined value of 0.1 used in the calculation /Hökmark and Fälth 2003/. This would give a temperature drop of about 8°C rather than the 11°C calculated above.

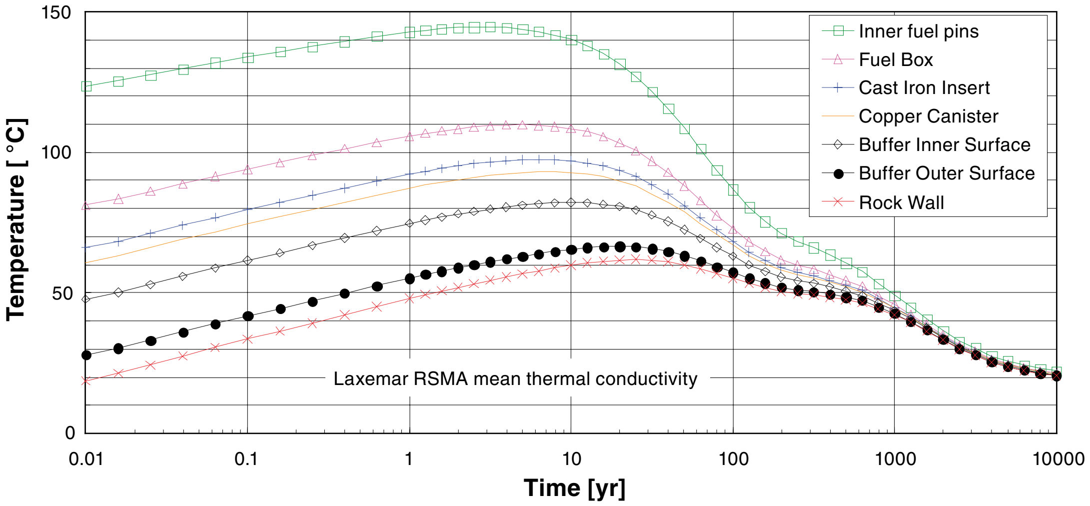


***Figure 3-10.** The thermal evolution for a number of points at canister mid-height for RSMA data given in Table 3-12 and Table 3-13. The corresponding figure for domain RSMM is almost identical.*

It was cautiously assumed that no groundwater is taken up by the buffer, since this would lead to an increased thermal conductivity and eventually to a closure of the gaps at the buffer interfaces. The thermal conductivity of the buffer was set to 1.1 W/(m·K), which is representative of the originally deposited material before water uptake /Hökmark and Fälth 2003/. The gap between the buffer and the wall of the deposition hole is, in this calculation, assumed to be empty and to have a width of 0.03 m. This can be seen as representative also of a 0.05 m gap filled with bentonite pellets, a design that is currently being considered to mitigate effects of potential spalling at the Laxemar site. The treatment neglects the presence of the tunnel backfill above the deposition hole, but this has been demonstrated to influence the critical temperature only marginally /Hökmark and Fälth 2003/.

#### *Sensitivity analyses*

Figure 3-11 shows the distribution of canister and buffer peak temperatures for a probabilistic calculation with all data taken from Table 3-13 and Table 3-13. These distributions essentially reflect the spatial variability of rock thermal conductivity at the canister scale. The figure shows the results of 10,000 realisations. For rock domain RSMA the highest peak temperatures obtained for the buffer and the canister were 91°C and 101°C, respectively. For rock domain RSMM, the corresponding temperatures are 87°C and 98°C. This suggests that the peak temperature criterion for the buffer will not be exceeded when the spatial variability of the rock thermal properties is taken into account. It is furthermore noted that there is a considerable margin to the 100°C criterion for the peak buffer temperature.

Figure 3-12 shows how the peak temperatures vary with the centre-to-centre spacing of the canisters in the two domains, assuming the minimum thermal conductivity for the domains, i.e. the lower truncation limits for the distributions as discussed above. Note that the results are very similar for the two domains since they both have lower truncation limits of 2.2 W/(m·K). The results suggest that there is a margin in the suggested canister spacing in both domains (7.2 m and 8.1 m) with respect to the buffer peak temperature criterion, thereby suggesting a margin for the overall space requirements of the repository. In fact, even a canister spacing of 6 m would be sufficient for fulfilling the thermal requirement on the buffer.

### 3.4.4 Safety implications

The previous sections show that a repository could be adapted to the Laxemar subarea meeting the thermal *requirements.* Furthermore, the relaxed temperature requirements, see Section 3.4.1, implies that, despite the rather low thermal conductivity at the site, the canister separation distances suggested in the repository layout are more than sufficient. More specifically the following quantitative conclusions are drawn.

- The distribution of canister and buffer peak temperatures for a probabilistic calculation considering the spatial variability of the thermal properties showed that, for rock domain RSMA the highest peak temperatures obtained for the buffer and the canister were 91°C and 101°C, respectively. For rock domain RSMM the corresponding temperatures are 87°C and 98°C. This suggests that the peak temperature criterion for the buffer will not be exceeded. (Furthermore, the present layout would also be almost sufficient for the previous temperature criterion of 100°C on the canister outer surface to be fulfilled).
- There is also a considerable margin to the 100°C criterion for the peak buffer temperature. In fact, even a canister spacing of 6 m would possibly be sufficient for complying with the thermal requirement on the buffer.

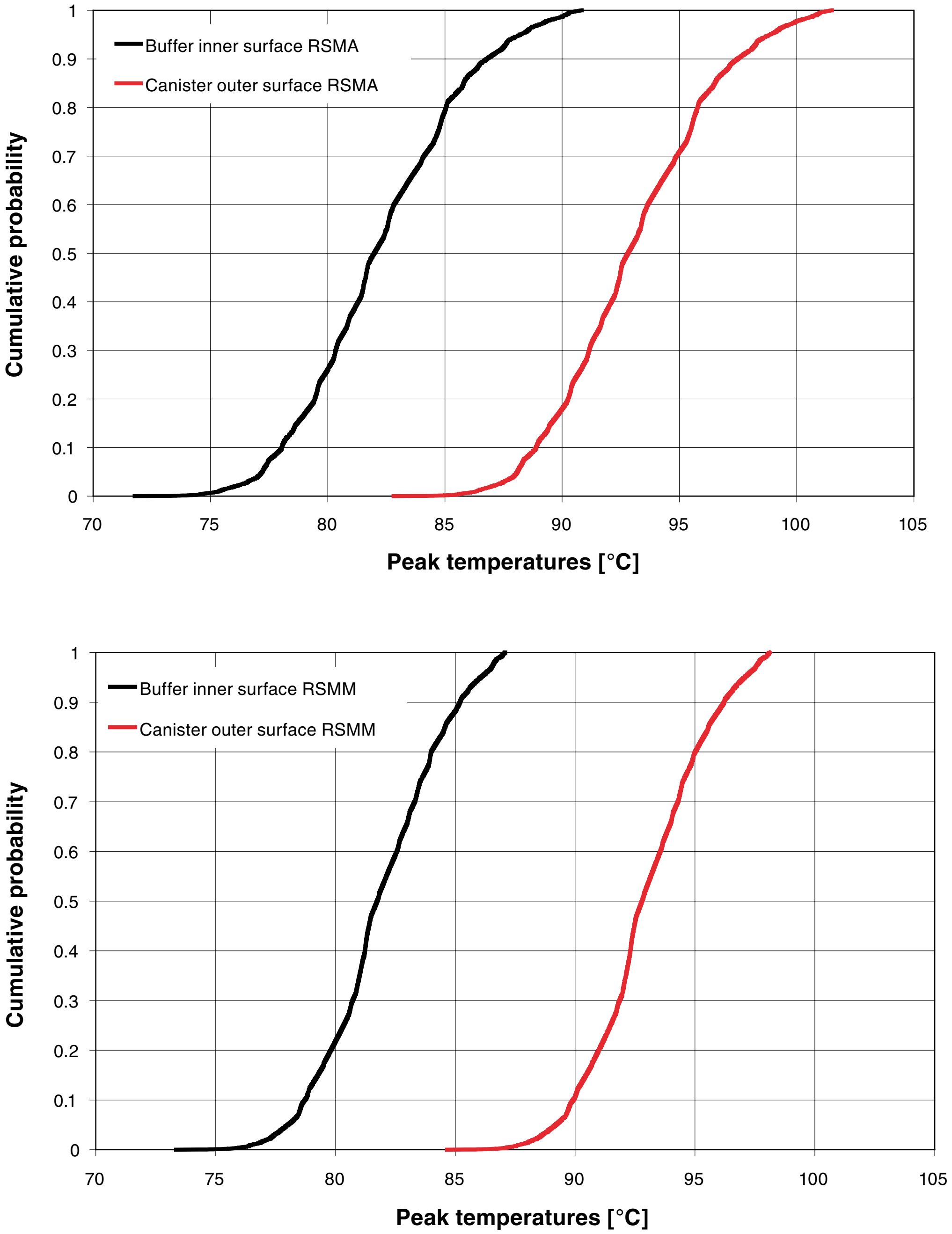
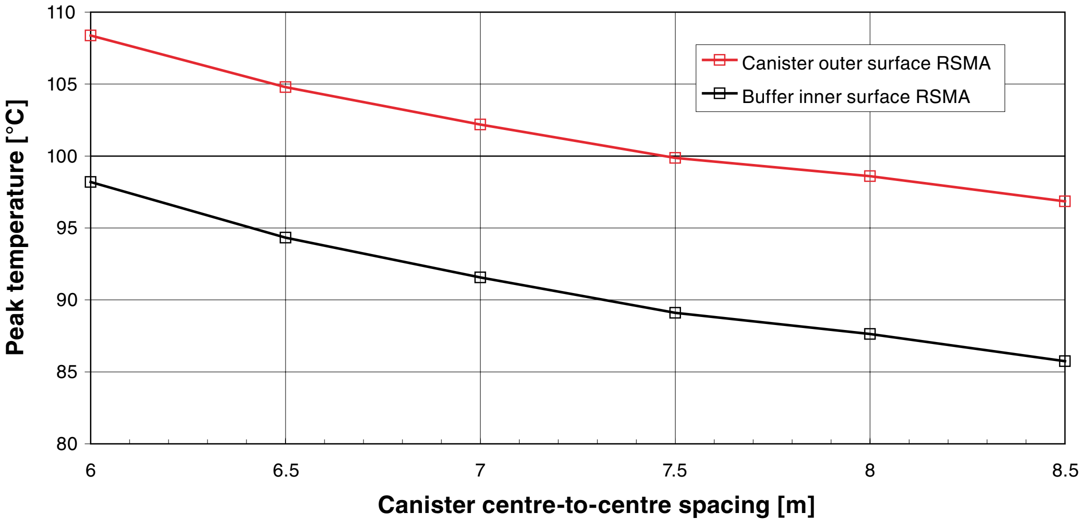


***Figure 3-11.*** *Probabilistic evaluation of the effect on buffer and canister peak temperatures of variability in rock thermal conductivity (upper: RSMA, lower: RSMM). Other data as in Table 3-13.*



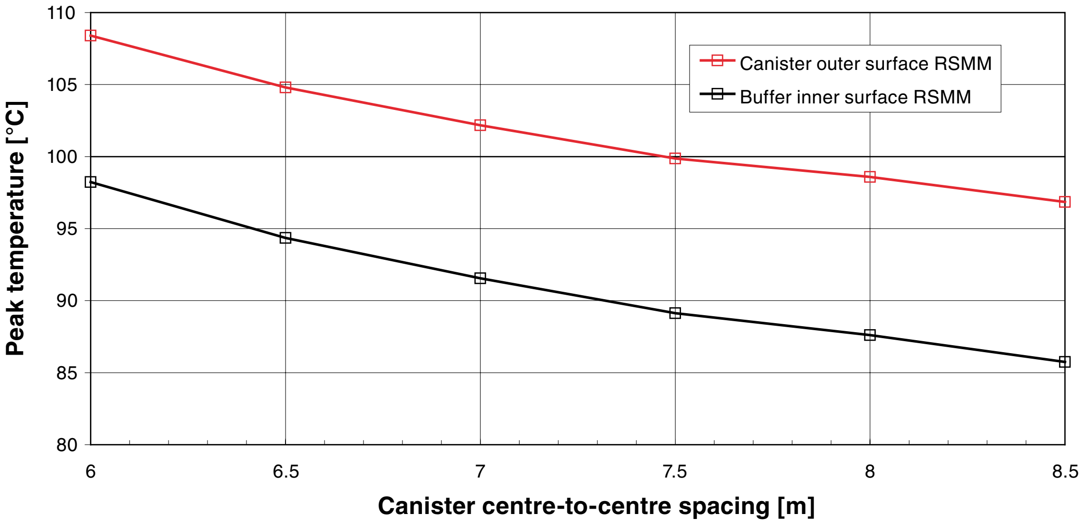


***Figure 3-12.*** *Sensitivity of canister and buffer peak temperatures to the canister centre-to-centre spacing (upper: RSMA, lower: RSMM). Note that the minimum thermal conductivity is assumed for each rock domain. Other data as in Table 3-12 and Table 3-13.*

Even if the thermal requirements and preferences are met, further reduction of uncertainties in the spatial variability and scaling of thermal conductivity would allow for a more efficient design. In order to justify a significant reduction of the canister separation distance making the layout more efficient, more representative data from the rock types in the repository volume are needed. The planned data and modelling envisaged in Chapter 12 and 13 in SDM L1.2 are considered justified and would most likely allow for a sufficiently well defined layout after the site investigation phase. In addition, a more detailed adaptation of the layout to the local thermal properties could possibly be made during the detailed investigation phase.

## 3.5 Hydraulic analyses

The hydraulic properties of the rock, i.e. the conductivity of the fracture systems and the driving forces, control the amount, rate and distribution of the groundwater flow in the rock. It is relatively easy to bound the driving forces, as they are essentially controlled by the elevation differences, i.e. topography, whereas the conductivity of the rock can vary substantially and thus needs to be assessed by measurements. Groundwater flow is important for safety, since groundwater flow is essentially the only pathway through which radionuclides could migrate from breached canisters into the biosphere. Groundwater flow also affects the composition of the groundwater in a potential repository volume and hence the stability of the engineered barriers.

### 3.5.1 Criteria and other safety considerations

#### *Previously set criteria*

The suitability criteria, as set out by SKB in /Andersson et al. 2000/, directly related to the hydraulics of the site, concern the conductivity (or rather transmissivity distribution) of fracture zones and of the fractures.

Generally, low groundwater flow implies more stable chemical conditions and better retention of radionuclides compared with a situation with high groundwater flow. It is therefore a *requirement* that deposition holes are not positioned too close to regional or local major fracture zones. An exception can be made from this requirement if it can be shown that the conductivity of the zone does not deviate significantly from that of the rest of the rock mass.

It is stated as an advantage (i.e. *preference*) if a large portion of the rock mass in the deposition area has a hydraulic conductivity $K < 10^{-8}$ m/s (on a 30 m scale), as such low conductivity would imply high "transport" resistance or F-values. (However, hydraulic conductivity alone is insufficient for determining the F-value and more recent thinking shows that a better criterion would be based on fracture transmissivity. For example, as shown in Section 3.7.3 a fracture of $T < 10^{-7}$ m$^2$/s would imply a transport path with $F > 10^4$ m/yr)[5]. For these reasons, /Andersson et al. 2000/ suggested that a large fraction of hydraulic conductivity values interpreted for the rock mass, during the site investigation, should have a values $< 10^{-8}$ m/s. Otherwise, there would be a need for local detailed adaptation of the design if the safety margin were to be met.

From a repository engineering perspective, it is also advantageous to have a low hydraulic conductivity around the deposition holes, as this would limit the inflow of water into those holes during deposition, thus simplifying the deposition procedures. For repository engineering considerations, it is also stated that deformation zones that need to be passed through during construction should have sufficiently low conductivity that passage can take place without problems. This would generally mean zones with transmissivity $T < 10^{-5}$ m$^2$/s or zones that are not wide and clay-filled. If such zones are encountered during the site investigation there should be an increased attention to impacts of, and problems with, grouting and other construction-related aspects. However, less transmissive zones would also need to be grouted.

The groundwater flow is also determined by the driving force, which for constant density groundwater can be expressed as the hydraulic gradient. (If there is large density variation

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[5] A simple justification for the preference value of $K < 10^{-8}$ m/s is suggested in the suitability criteria document /Andersson et al. 2000/. An updated version of these arguments is provided in Section 3.7.3, subsection: "First order evaluation of transport resistance".

buoyancy effects needs also to be taken into account). Data on the boundary conditions, e.g. hydraulic gradient, or data on recharge/discharge areas are needed primarily for building credible groundwater models. No requirements were set, but rather arbitrarily it was suggested that there is an advantage if the local gradient is less than 1 percent at repository level (but with no additional advantage if it is lower) and that areas with an unsuitably high gradient (much greater than 1 percent) should be rejected during the feasibility study phase. No criteria were given for the Site Investigation phase.

#### *Additional considerations*

As already explained above, the preference values for hydraulic conductivity on the canister scale are based on rather simplistic reasoning. If anything, the suggested limits appear a little pessimistic.

A more useful criterion would be the distribution of Darcy velocity and transport resistance F along potential migration paths. A full assessment of these entities is rather resource demanding and could only be meaningfully carried out within a safety assessment. However, estimates of the distribution of these quantities using the regional-scale numerical groundwater flow model developed as a part of the SDM is more straightforward. Such an analysis is reported in Section 3.7.

### 3.5.2 Hydraulic properties and effective values of conductivity

As further explained in Chapter 8 of SDM L1.2, the conceptual hydrogeological model of the site implies that only fractures and fracture zones could conduct water, although the rock matrix may be connected to the flow system by diffusion. In the model, the conductive features are divided between Hydraulic Conductor Domains (HCD), which essentially coincide with the deformation zones in the geological model, and Hydraulic Rock Domains (HRDs) representing the rock mass between the HCDs. The hydraulic properties of the HRDs are modelled as hydraulic DFN models, with the geometry based on the geometry of the geological DFN model, and with added hydraulic properties.

#### *Transmissivity of the deformation zones*

The deterministic deformation zones in the geological model, see Section 3.2.4, are all assumed to be HCDs in the hydrogeological model. Hydraulic tests confirm that the deformation zones usually are more conductive than the surrounding rock. As further discussed in L1.2, the measured hydraulic conductivity of the deformation zones, assessed by dividing the zone transmissivity by the zone thickness, is about an order of magnitude larger than the hydraulic conductivity of the rock mass where test sections intersected by deformations zones are excluded. However, some HCDs in the current model may have low transmissivity (and hydraulic conductivity). Furthermore, many of the deformation zones are not tested hydraulically.

To estimate the properties of the HCDs in the hydrogeological model generally results from transient pumping or injection tests have been used. If there is a hydraulic test section in a borehole covering the entire length of what the responsible geologist considers to be the zone, the corresponding test results have been used, instead of summing up the transmissivities for shorter test sections over this zone. With this description, the deformation zone is described as a single feature, whereas in reality it is made up of many small fractures contributing to a complex flow path pattern. Using this description to estimate the transport resistance, see Section 3.7.3, of the zone would result in a lower value than in reality, since no single migration path would have the high value represented by the sum of transmissivities of the paths in zone. Using the detailed hydraulic data could result in a more realistic, and less pessimistic, description of the zone, but this approach would arguably be more difficult to defend in light of the limited amount of detailed data from different locations in the same zone.

Table 8-9 of SDM L1.2 presents the transmissivity data evaluated for the HCDs. Such test data exists for about two thirds of the high confidence zones and for a few of the medium confidence zones in the local model volume, but there are few instances with more than one measurement from the same zone. HCDs with no hydraulic tests have been assigned the geometric mean value ($1.2 \cdot 10^{-5}$ $m^2/s$) for all HCDs and with an assumed geological thickness of 20 m. It can be observed that this mean value of T is higher than that measured at the intercepts of many of the high confidence deformation zones. Furthermore, many of the low confidence zones in the local model area have shorter trace length on the surface compared to the high and medium confidence deformation zones. Consequently, it not unlikely that many of the low confidence zones would be less transmissive than the high and medium confidence deformation zones, i.e. that the current model grossly exaggerates the transmissivity of many of the deformation zones.

The data also possibly suggest a decreasing transmissivity with depth as indicated by Figure 3-13. Different depth trend curves are fitted to the data. As can be seen in the figure the confidence limits for mean Log10(T) is wide for all thee depth intervals, demonstrating that the inferred depth trend of the transmissivity is very uncertain due to sparse data for the deformation zones. Furthermore, there are few measurements from the same deformation zones, so the differences in T-values could be coincidental. Apart from zones being different, this could also be an indication of the spatial variability within individual zones, although estimates of the latter would require multiple measurements in the same zone.

The geometry and connectivity of the deformation zones is uncertain. There are only few interference tests in the Laxemar subarea. In principle, this uncertainty affects transport paths and the integrated evaluation in conjunction with hydrogeochemistry, but the actual importance is tested by analysing cases with and without the low confidence zones.

Spatial variability of transmissivity in the deformation zones is uncertain. Only a few deformation zones have been subject to more than one flow test. Nevertheless, the combined data from many zones suggest a depth trend, in which transmissivity decreases with depth. The overall depth trend is used as the basic model. The spatial variability is estimated based on the overall spatial variability in data as measured in different zones, but the main case analysed in the flow simulations assumes no spatial variability apart from the depth trend. Alternative cases with different transmissivity distributions are also formulated. The calibration against hydrogeochemistry data (palaeohydrogeology, see Chapter 9 of SDM L1.2 and also Section 3.6.2 below) provides some means of testing the current model and the hydrogeological model can reproduce the overall characteristics of the measured groundwater composition, although not no one to one fit. It appears that the current model provides a reasonable representation of the overall hydrogeological situation.

### *Hydraulic properties of the rock mass*

In assessing the hydraulic properties of the rock mass, the data were first explored and used to develop an overall conceptual model of the distribution of hydraulic properties in the subarea. As discussed in Chapter 8 of SDM L1.2, the hydraulic data from the boreholes suggest that the rock mass at the Laxemar subarea has a depth dependent conductivity, but the interpretation is uncertain.

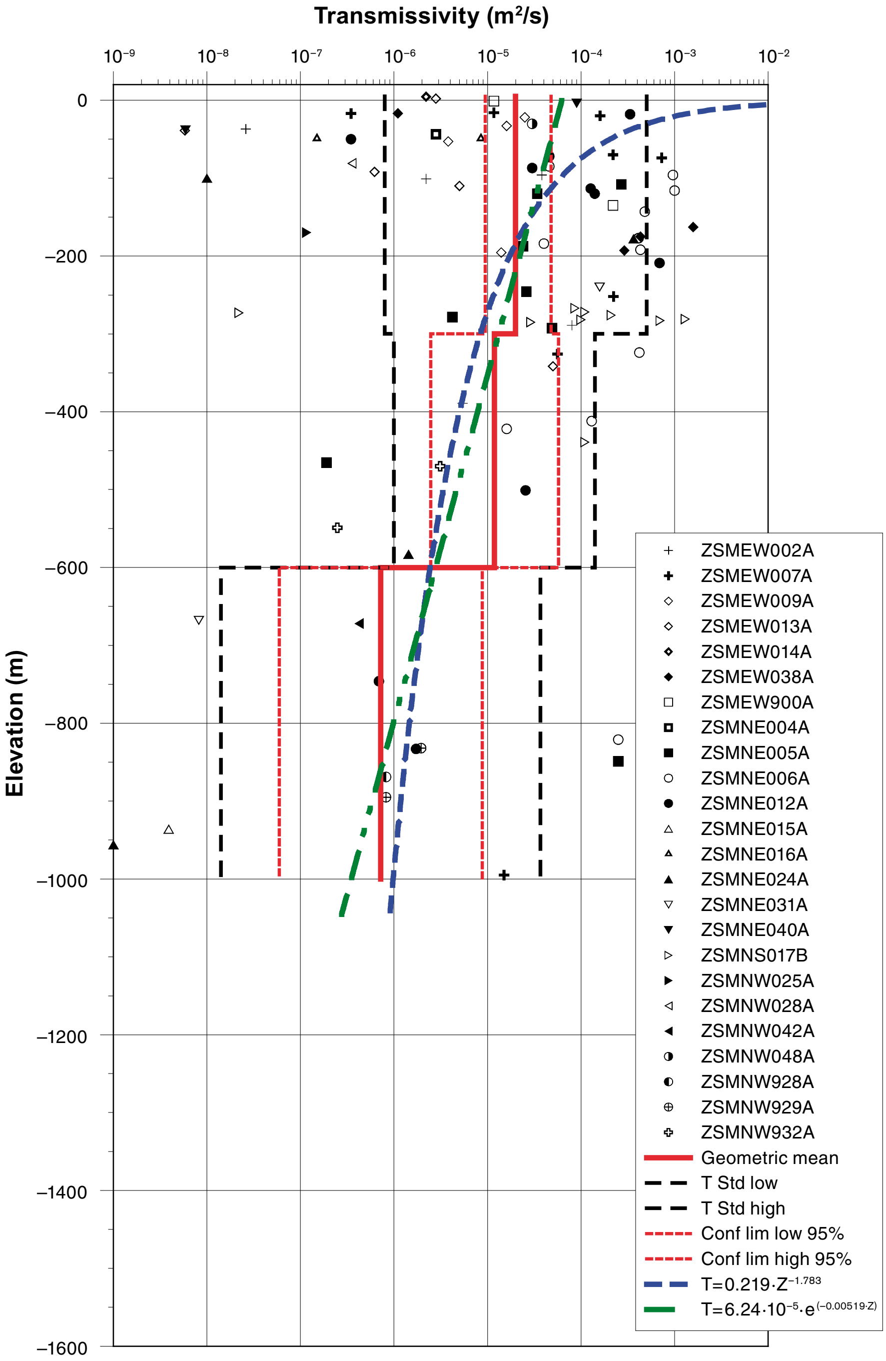

***Figure 3-13**. Possible depth trend of the transmissivity in HCDs (Figure 8-15 of SDM L1.2).*

Table 3-14 presents some basic fracture frequency data outside the deformation zones. $N_{PFL}$ is the number of flow anomalies in the connected network of flowing features above the lower measurement limit of the Posiva Flow Log method (PFL) and $P_{10PFL}$ ($m^{-1}$) is the frequency of such features along the borehole section. The table also provides the mean and standard deviation of $Log_{10}(T)(m^2/s)$ for the different borehole sections. As noted in SDM L1.2 Chapter 8, the lower measurement limit of the PFL method is not a threshold with a fixed magnitude but varies in space, in and between boreholes, depending on the in situ borehole conditions. However, $P_{10PFL}$ may still be regarded as a good measure of the frequency of fractures with a transmissivity of $10^{-9}$ $m^2/s$ or larger. As shown in Section 3.7.3, these data are directly used to a make a first order evaluation of the distribution of transport resistance in the rock mass, without a need for elaborate DFN-modelling.

**Table 3-14. Basic hydraulic data measured by the Posiva Flow Log (PFL). Measurements made in sections belonging to HRDs are excluded. (Based on Table 8-7 SDM L1.2).**

| Bore-hole | Upper elevation limit (m) | Lower elevation limit (m) | $N_{PFL}$ | $P_{10PFL}$ ($m^{-1}$) | Lower meas. limit $Log_{10}$ T ($m^2/s$) | Mean Log10(T) ($m^2/s$) | Std $Log_{10}$(T) ($m^2/s$) |
|---|---|---|---|---|---|---|---|
| KLX02 | –186 | –300 | 32 | 0.31 | –10 to –8.3 | –7.23 | 0.95 |
| | –300 | –700 | 21 | 0.052 | –10 to –8.3 | –7.93 | 0.75 |
| | –700 | –1,372 | 21 | 0.043 | –10 to –8.3 | –7.77 | 0.89 |
| KLX03 | –79 | –300 | 25 | 0.11 | –9.8 to –8.2 | –7.81 | 1.05 |
| | –300 | –700 | 15 | 0.038 | –9.8 to –8.2 | –7.87 | 0.70 |
| | –700 | –944 | 3 | 0.017 | –9.8 to –8.2 | –7.44 | 0.94 |
| KLX04 | –75 | –300 | 44 | 0.20 | –9.6 to –8.7 | –7.01 | 0.85 |
| | –300 | –700 | 51 | 0.13 | –9.6 to –8.7 | –7.34 | 0.77 |
| | –700 | –957 | 1 | 0.0063 | –9.6 to –8.7 | – | – |

As can be seen from the table, $P_{10PFL}$ decreases by about a factor of 6 below –300, in KLX02, but only be a factor of 2–3 in KLX03 and by a factor of 2 in KLX04. There is less change in the mean transmissivity with depth, but there is a about a factor of 3 lower mean transmissivity in KLX03 than in KLX04. These data indicate that the hydraulic characteristics may depend on depth and on rock domain, but also illustrate the strong spatial variation of the hydraulic properties. There is a about one order of magnitude standard deviation. The noted difference between the boreholes may not be valid.

Figure 3-14 shows results of 100 m injection test data from the Laxemar subarea, where data representing the deterministically interpreted deformation zones are excluded. Two depth trend functions, a power law and an exponential model, were fitted to the mean values. There seem to be a slight decrease in hydraulic conductivity with depth, but one should also observe that there are rather few observations in the elevation intervals 100 m to 300 m in the Laxemar subarea, and some of the data may be directly or indirectly affected by the proximity of deformation zones. Anyway, it seems that there is a zone close to the surface with higher hydraulic conductivity. This zone of increased hydraulic conductivity reaches down to 300 m to 400 m depth in both KLX02 and KLX04, but may be shallower, 100 m to 300 m, in other boreholes.

There is also a potential difference in mean hydraulic conductivity between rock types. Granite, medium- to coarse-grained and Granite and Fine grained granite are the most permeable. Ävrö granite has a lower hydraulic conductivity. The lowest hydraulic conductivity is found in the more basic rock types. For this reason the hydraulic description distinguishes HRDs with different properties. Within the Laxemar subarea these HRDs relate to the geological Rock Domains in the following way:

- HRD(A): Rock domains RSMA and RSMBA within the Laxemar subarea.
- HRD(D,E,M): Rock domains RSMD, RSME and RSMM within the Laxemar subarea.

Additional HRDs are suggested outside the Laxemar subarea.

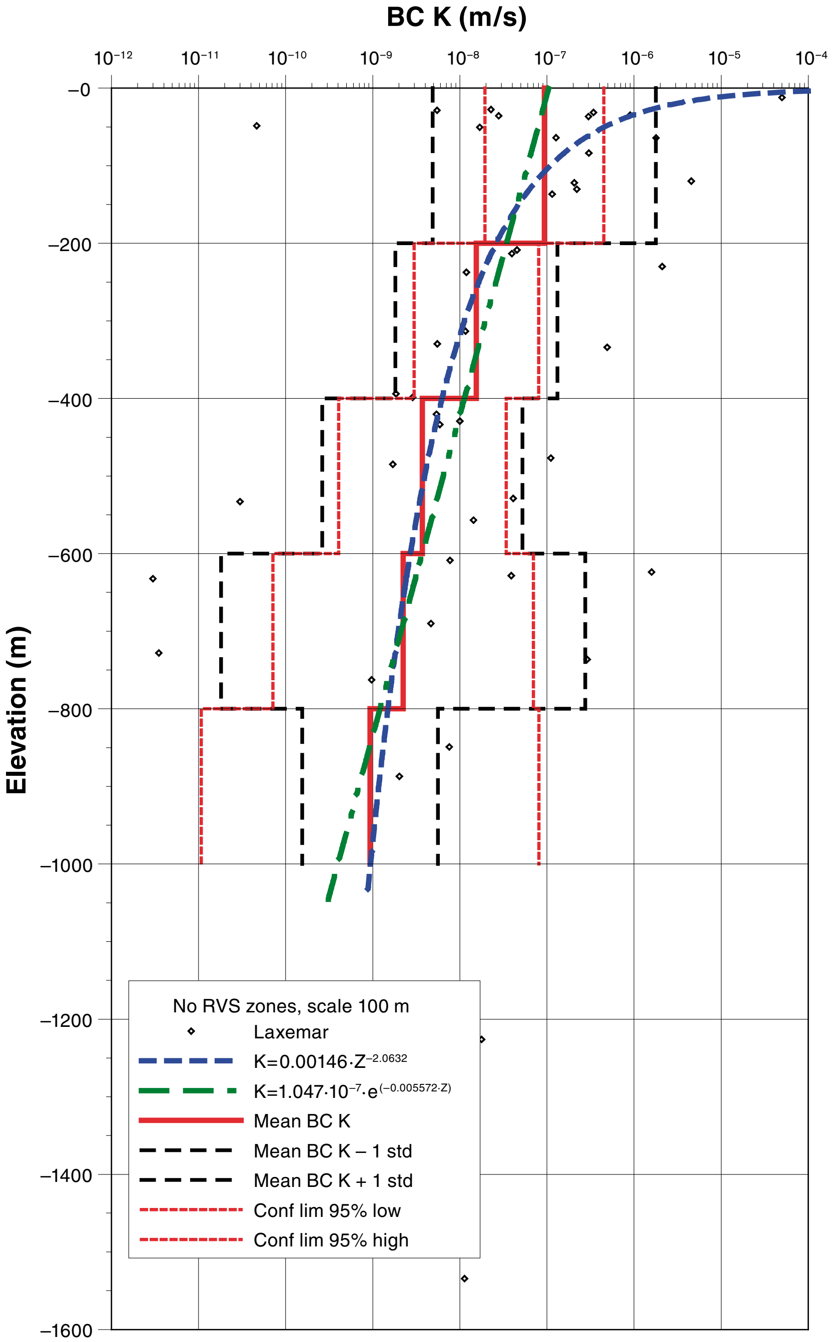

***Figure 3-14****. Depth trend of the hydraulic conductivity in HRDs. Test scale 100 m. Data, statistics and depth trends based on data from the Laxemar subarea alone. Data representing deterministically interpreted deformation zones are excluded. Based on Boreholes HLX01–09, -32, KLX01–KLX06 (In KLX05 and KLX06 , only data from WLP measurements are included). BC= Best choice value (Figure 8-20 in SDM L1.2).*

Using this overall description, the hydraulic properties of the rock mass are then described by means of a hydraulic discrete fracture network model (Hydro-DFN). The analyses were mainly made by /Hartley et al. 2006/. In addition /Follin et al. 2006/ studied the key assumptions in the methodology in the underlying geological DFN model and addressed how these propagate into the hydraulic DFN modelling. The following boreholes have defined the properties of the HRDs:

- KLX04: HRD(A).
- KLX03: HRD(D,E,M).

The hydraulic analysis of the borehole data involved simulations with the DFN models in order to match the flow data measured in the boreholes. The main assumption was to fully correlate fracture size and transmissivity, setting log(T)=b·log(a·r), where r is the fracture radius. However, alternative models, with no correlation, log(T)= N(μ,σ)[6], or with some correlation, log(T)=b·log(a·r)+ N(μ,σ), are also applied to the data. These alternatives results in quite different block properties and cannot be excluded at this time. The resulting hydraulic DFN models for defined HRDs of the Laxemar subarea are illustrated in Figure 3-15.

A variant of the Hydro DFN base case, *HydroDFN regional case*, was made during the calibration of the regional model, cf Section 8.5 of SDM L1.2. For the regional modelling reference case, the underlying hydraulic DFN model was initially based on the Hydro DFN base case with a semi-correlated T model. However, during the regional modelling studies, modifications were made to the hydraulic DFN prescription to achieve a better calibration against borehole hydrogeochemistry. The use of homogeneous models for hydraulic conductivity using depth dependency trends based on the PSS data all resulted in a poor

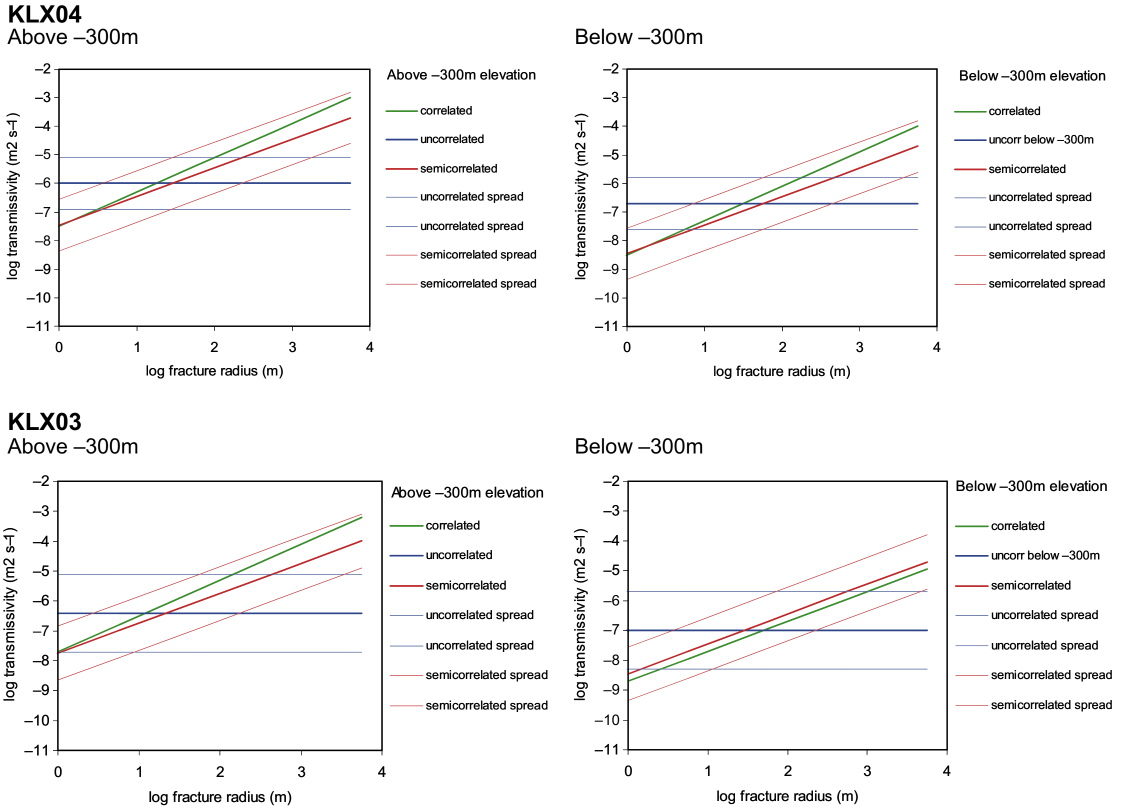

*Figure 3-15. Transmissivity model relationships for KLX04 and KLX03, above and below –300 m. (Figure 8-27 of SDM L1.2 taken from /Hartley et al. 2006/.)*

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[6] N(μ,σ) is the normal distribution with mean μ and standard deviation σ.

match against the hydrogeochemical data. For such models, a calibration could only be achieved using a hydraulic conductivity in the deep rock more than an order of magnitude less than measured values. Using the Hydro DFN base case gave interval conductivities consistent with the hydraulic injection test data (PSS) 100 m interval data, and when anisotropy was introduced by reducing the transmissivity in the subvertical fracture sets Set_A and Set_B, a reasonable match with hydrogeochemistry was obtained.

Some important conclusions from the results of the hydraulic DFN modelling are given in SDM L1.2:

- At least in borehole KLX04 there are a number of high transmissivity sections and high flow rates that cannot be described by the model. This can to some extent be related to the definition of what parts of the borehole (KLX04) should be considered as being in a deformation zone (where the transmissivities are summed up to represent one feature). Possibly some flow anomalies near the defined deformation zones should be considered to be part of those deformation zone. However, this may not be the sole explanation, and needs be the subject of continued analysis in future modelling.
- If the input fracture intensity ($P_{32}$) is adjusted, all three transmissivity models parameter settings can be fitted such that the model simulations generate flow rate distributions similar to the ones measured. However, the semi-correlated model seems to provide somewhat better match than the other transmissivity models.
- The noted variability in transmissivity between boreholes and the relatively few boreholes, implies uncertainty when extrapolating the statistics of a single borehole to larger volume (rock domain). This needs to be better explored.
- The PFL data can be correlated to individual fractures. These data give some indication that the subvertical sets Set_A and Set_B have a 0.5 to 1.0 orders of magnitude lower transmissivity than Set_C and Set_d. This concept was also successfully tried in the *Hydro DFN regional case*. However, at the moment these results are only to be regarded as indicative, being based on analysis of KLX04 data alone. Also, it should be understood that the importance of anisotropy may have been underestimated in opting for a simplified hydraulic DFN model with the same transmissivity relationships for all fracture sets.

Consequently, given these uncertainties and given the uncertainties in the DFN model the hydraulic DFN analysis should be seen as indicative only. More data from the rock mass of the potential repository volume are needed before it is meaningful to more elaborately try to bound the uncertainties and spatial variability of the rock mass hydraulic properties of the Laxemar subarea. Furthermore, the analysis needs to be supplemented by more robust arguments, such as those indicated in Section 3.7.3, under the heading “First-order analysis of transport resistance”.

### Effective values of hydraulic conductivity

The different alternative hydrogeological DFN models have been used to simulate effective values of hydraulic conductivity at different scales. The simulations were set up by generating discrete fracture networks in large blocks, applying simple boundary conditions, solving the groundwater flow and then averaging over different block sizes. This also allows assessment of potential block-scale anisotropy. For modelling reasons it was decided to assess block properties at the 20 m and 100 m scales, rather than at the 30 m scale set out in the criteria, but the 20 m scale values give a good representation also of the 30 m scale. It should also be remembered that hydraulic conductivity alone is insufficient for determining the transport resistance. The block conductivity values have limited relevance for performance.

Table 3-15 summarises the results of the block modelling for HRD(A) and Table 3-16 for HRD(D,E,M) in volumes below –300 m. In HRD(D,E,M), as can be seen from Table 3-16, more than 75% of the blocks at the 20 m scale have hydraulic conductivity below $10^{-8}$ m/s for all cases. In HRD (A) (see Table 3-15) a little more than 50% of the blocks at the 20 m scale have hydraulic conductivity below $10^{-8}$ m/s for the semi-correlated case, whereas the percentage is a little lower for the uncorrelated and correlated cases. This illustrates the potential difference between rock domains, as suggested by the data. However, the uncertainties are rather large, as discussed in the previous section, primarily due to the potentially poor representativity of the data at this stage.

**Table 3-15. Effective hydraulic conductivity for correlated, uncorrelated and semi-correlated transmissivity concepts for HRD(A), i.e. based on KLX04. Scale (cell size) recorded in metres. (Based on Table 4-2 in /Hartley et al. 2006/).**

| | | $\log_{10}(K_{eff})$ [m/s] | | | | |
|---|---|---|---|---|---|---|
| **T model** | **Scale** | **10%** | **25%** | **50%** | **75%** | **90%** |
| Correlated | 20 | –9.64 | –9.12 | **–8.00** | –6.85 | –6.64 |
| Correlated | 100 | –8.62 | –8.30 | **–7.93** | –7.54 | –7.22 |
| Uncorrelated | 20 | –8.78 | –8.36 | **–7.90** | –7.58 | –7.29 |
| Uncorrelated | 100 | –8.76 | –8.55 | **–8.22** | –7.89 | –7.63 |
| Semi-correlated | 20 | –9.76 | –9.10 | **–8.34** | –7.77 | –7.49 |
| Semi-correlated | 100 | –9.08 | –8.72 | **–8.24** | –7.74 | –7.29 |

**Table 3-16. Effective hydraulic conductivity for correlated, uncorrelated, semi-correlated transmissivity concepts for HRD(D,E,M), i.e. based on KLX03. Scale (cell size) recorded in metres. (Based on Table 4-4 in /Hartley et al. 2006/).**

| | | $\log_{10}(K_{eff})$ [m/s] | | | | |
|---|---|---|---|---|---|---|
| **T model** | **Scale** | **10%** | **25%** | **50%** | **75%** | **90%** |
| Correlated | 20 | low | –12.17 | **–9.25** | –8.32 | –7.89 |
| Correlated | 100 | –10.67 | –9.81 | **–9.22** | –8.73 | –8.43 |
| Uncorrelated | 20 | low | –14.63 | **–10.24** | –9.06 | –8.50 |
| Uncorrelated | 100 | –10.71 | –10.02 | **–9.39** | –8.85 | –8.30 |
| Semi-correlated | 20 | low | –16.60 | **–10.29** | –8.58 | –7.84 |
| Semi-correlated | 100 | –10.58 | –9.88 | **–9.14** | –8.34 | –7.87 |

### 3.5.3 Groundwater flow calculations and particle discharge points

Based on the hydraulic property description, the SDM L1.2 also presents transient, density dependent, groundwater flow calculations in an equivalent porous medium representation at a regional scale. Flow paths are assessed for the velocity field simulated for the present day. A much more extensive set of simulations will be carried out in SR-Can.

The analyses are made by particle tracking, with particles released from an area approximately located within the Laxemar subarea at 500 m depth. Particles were also released from the Simpevarp subarea, see Figure 3-16. An example of discharge points is shown in Figure 3-17. The results of the flow simulations have also been compared with the measured chemical data, see further Section 3.6.2.

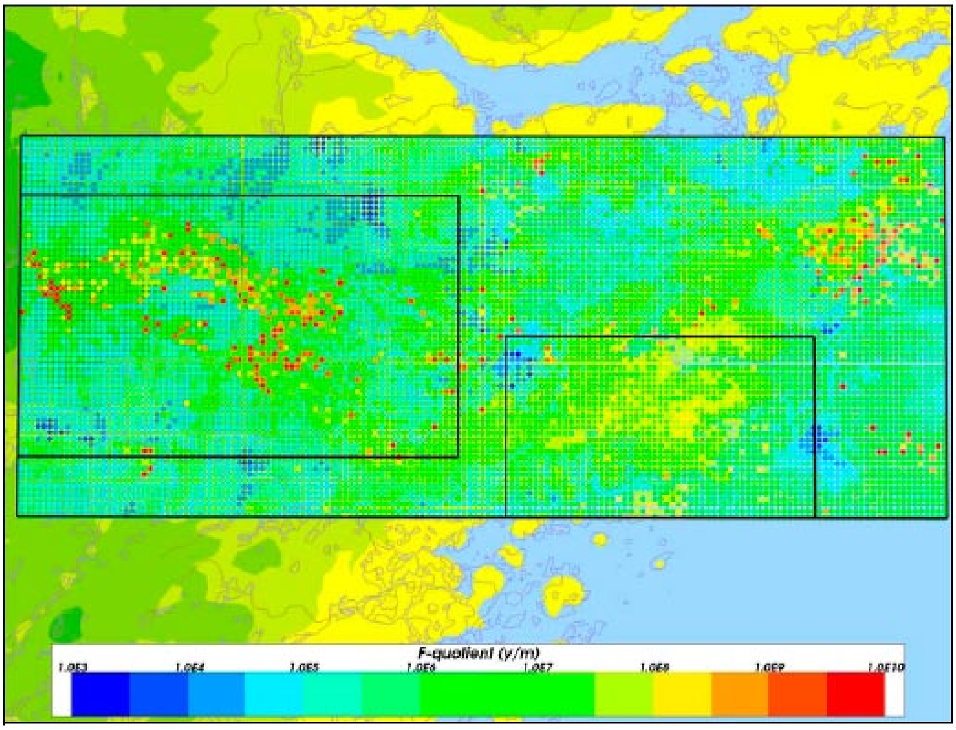

***Figure 3-16.*** *Particle starting locations. The Laxemar (left) and Simpevarp (right) release areas are shown as smaller black rectangles within the local model area (from /Hartley et al. 2006/, Figure 9-1).*

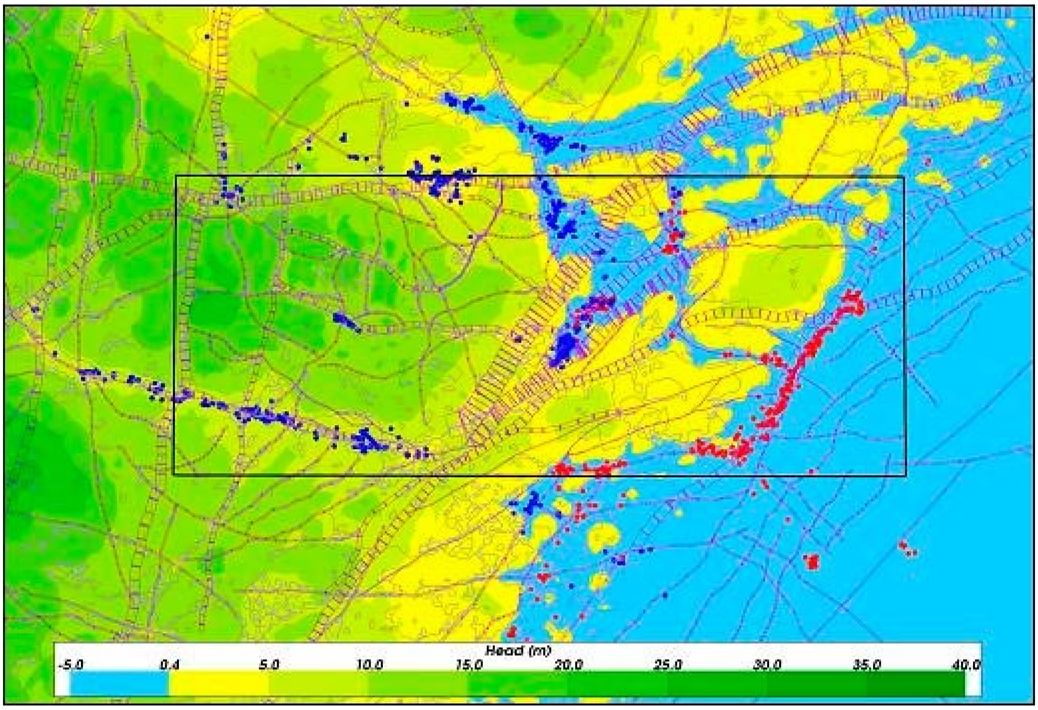

***Figure 3-17.*** *Close-up view of particle exit locations in the local-scale release area for the reference case of /Hartley et al. 2006/. Particles released from the Laxemar release-area are coloured in blue and particles from the Simpevarp release-area are coloured in red. The local-scale model release area (black rectangle) is shown for orientation. Because of the limited view, not all particles are shown in the picture. (From /Hartley et al. 2006/ Figure 9-4).*

The flow model has also been used to predict the salinity and distribution of different water types as identified in the hydrogeochemical modeling, see Section 3.6.2. Figure 3-18 shows a comparison of simulated and measured salinity in KLX01, KLX02, KLX03 and KLX04 for the reference case of the hydrogeological model. It is noted that overall distribution of salinity for the series of boreholes are generally good for the KLX and KSH boreholes, but there is certainly not a one to one fit. For example, the salinity measured for KLX01 at –220 m is calculated to occur at –500 m. The observed salinity for KLX02 at –390 m corresponds to the one calculated for –800 m. For KLX04 the measured salinity at –500 m is predicted to occur at –800 m. This could possibly be due to a too high conductivity in the hydrogeological model. The model also seems to simulate some moderate flushing of the deep Brine in KLX02, below about –1,200 m, suggesting possibly a little to high (vertical) conductivity at depth. The simulations nevertheless indicate the relatively fast migration of non-reactive species from the near surface to depth.

In addition to the reference case /Hartley et al. 2006/ analyzed several variants. Based on these SDM L1.2 draw the following conclusions from the regional flow analyses:

- The path lengths of the released particles are generally quite short. Localised flows are present as a result of the topography and the heterogeneous bedrock. Most released particles exit inside, or very close to, the local scale model area, including the two release areas. The exit locations are located close to the shoreline and in the valleys with lower topographic elevation in the area.
- Due to the topographic elevation, most of the Laxemar release-area is beneath a recharge area. The discharge areas are located close to the shoreline and in a few valleys onshore. The recharge areas (obtained by back-tracking of particles in the velocity-field until they reach the surface), are associated with several topographic highs both inside and outside the local-scale release-area. The recharge areas are found well inside the model domain suggesting that the regional water divides are an appropriate choice. The area of recharge for the Laxemar release area is, for the most part, directly above the site. A few recharge areas that influence the Laxemar site are located at hills several kilometres to the west and southwest. All the major islands (Äspö, Ävrö and Hålö) together with the Simpevarp peninsula act as recharge areas.

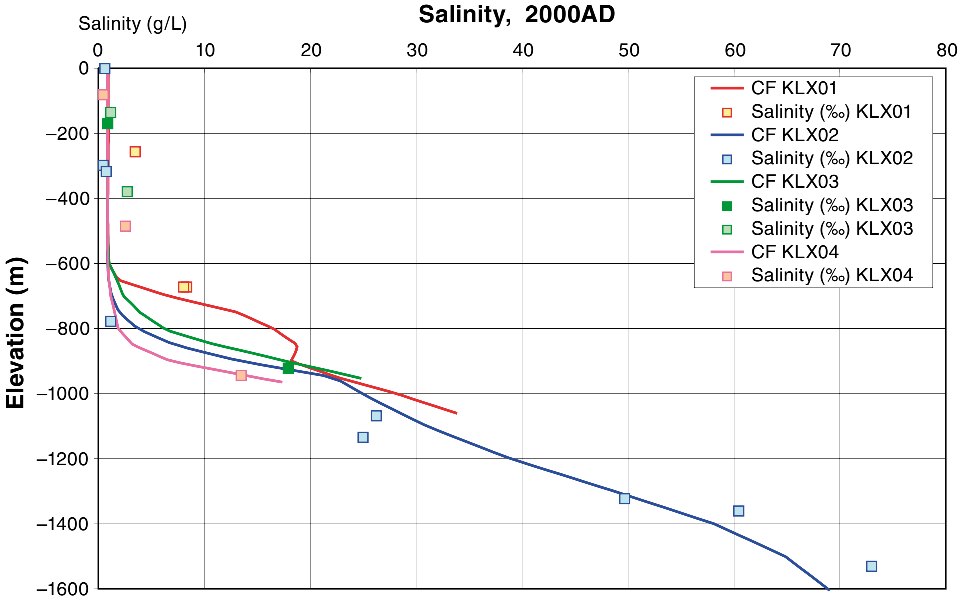

***Figure 3-18.** Comparison of simulated and measured salinity in KLX01, KLX02, KLX03 and KLX04 for the reference case of the hydrogeological model. The simulated salinity in the fracture system is shown by solid lines, and the data by points. Only representative data are shown, (Figure 9-36 of SDM L1.2).*

- The predominant exit locations of the particles released from the Laxemar subarea are the valleys north and south of the Laxemar release area and close to the shoreline between Äspö and Hålö. There is only one very minor discharge area at the centre of the Laxemar area associated with a small stream.
- The model is moderately sensitive to the top boundary conditions. The case with the lowest water table gives the best match to the hydrogeochemistry data at the boreholes. However, in terms of flow-path statistics and exit locations, there are only small differences in results based on the three boundary conditions.

For more detail, see Chapter 8 of SDM L1.2 and /Hartley et al. 2006/.

### 3.5.4 Safety implications

The previous sections show that the target area at Laxemar subarea meets the hydraulic requirements. Also, the preferences are judged to be met, although the relatively high and uncertain permeability distribution at potential repository depth should be noted. More detailed conclusions are set out below.

- The requirement that deposition holes should not be positioned near regional or local major fracture zones is fulfilled by the geological requirement (see Section 3.2).
- As seen in Section 3.5.2 more than 75% of the blocks at the 20 m scale in HRD(D,E,M) have hydraulic conductivity below $10^{-8}$ m/s for all cases. However, in HRD (A) only a little more than 50% of the blocks at the 20 m scale have hydraulic conductivity below $10^{-8}$ m/s for the semi-correlated case, and the percentage is even a little lower for the uncorrelated and correlated cases. This illustrates the potential difference between rock domains, as suggested by the data. However, the uncertainties are rather large, as discussed previously primarily due to the potentially poor representativity of the data, and the validity of the difference between domains is uncertain. This means that there is some uncertainties to whether the preference on low hydraulic conductivity is met. However, as explained above, the preference values for hydraulic conductivity at the canister scale are based on rather simplistic reasoning. A more useful criterion would be the distribution of Darcy velocity and transport resistance, F, along potential migration paths, see Section 3.7.
- There is a wide transmissivity range in the deformation zones, and especially at shallow depths, there are several deformation zones with transmissivity, T, above $10^{-5}$ $m^2/s$. If there is a need to pass through these zones during the access tunnel construction, the engineering implications will have to be carefully assessed. However, re-analyzing the experiences from the construction of the Äspö HRL shows that highly transmissivity zones can be passed also at great depths /Chang et al. 2005/.
- Particle tracks generated from the modelled current day groundwater flow suggest that there are rather short flow paths from the repository depth to local discharge areas (see Figure 3-17). The exit locations are close to the shoreline and in the valleys with lower topographic elevation in the area. Due to the topographic elevation, most of the Laxemar subarea is beneath a recharge area.

As explained above, the preference values for hydraulic conductivity at the canister scale are based on rather simplistic reasoning. A more useful criterion would be the distribution of Darcy velocity and transport resistance, F, along potential migration paths. Section 3.7.3 of this PSE present some estimates of the distribution of these quantities from first-order analyses now carried out as part of the site modelling and also by exploring results from the regional-scale numerical groundwater flow model, but a more elaborate evaluation lies outside the scope of this PSE.

Given the uncertainties in the hydraulic data and in the DFN model the hydraulic DFN analysis should be seen as indicative. There is a high variability of transmissivity within boreholes and the significance of the currently suggested depth dependence could be questioned. There is also high variability in transmissivity between boreholes, and the relatively few boreholes imply uncertainty when extrapolating the statistics of a single borehole to larger area, i.e. the appropriateness in attributing different hydraulic properties to different rock domains is not fully established. The importance of fracture sets at different orientations having different transmissivities may also have been underestimated. More data from the rock mass of the potential repository volume is needed before it is meaningful to more elaborately try to bind the uncertainties and spatial variability of the rock mass hydraulic properties of the Laxemar subarea. More detailed suggestions for how to reduce the uncertainties are given in the SDM L1.2.

## 3.6 Hydrogeochemistry

A stable and suitable groundwater composition is a prerequisite for the long-term stability of the copper canister and the bentonite buffer. Thus, the hydrogeochemistry directly affects the potential for isolation.

### 3.6.1 Criteria and other safety considerations

***Previously set criteria***

The suitability criteria, as set out by SKB in /Andersson et al. 2000/, directly related to the chemical conditions of the site essentially concern dissolved oxygen, pH, salinity or Total Dissolved Solids (TDS) and some other chemical parameters.

It is a *requirement* that the groundwater at repository depth does not contain dissolved oxygen, since dissolved oxygen could corrode the copper canister and thus threaten containment. Presence of oxygen at depth would be an indication of strongly anomalous groundwater flow and/or very poor reducing capacity in the rock. Groundwater with negative Eh, occurrence of Fe(II) or with occurrence of sulphide ($HS^-$) cannot, for chemical reasons, contain measurable amounts of dissolved oxygen, which means that the requirement is fulfilled if any of these indicators is present over the proposed repository domain. As a criterion for the site investigations, it is stated that groundwater from potential repository depth must exhibit a least one of these indicators. Otherwise the site should be abandoned.

The groundwater pH affects the stability of the bentonite and also affects radionuclide retention properties (sorption and solubility). There is no requirement, but there is a *preference* that undisturbed groundwater at repository level should have a pH in the range 6–10. This is assessed by checking whether quality assured groundwater samples taken below the 100 m level lie within the preferred range.

Groundwater salinity affects bentonite swelling. At the time of publication of the suitability criteria, experimental evidence led to a *required* limit of TDS < 100 g/L in order to ensure sufficient bentonite swelling. During site investigations, quality-approved measured TDS at repository level must meet this requirement. Occasional higher values can be accepted, if it can be shown that the water is located in volumes that can be avoided.

There are also *preferences* set for some other chemical parameters in the deep groundwater, namely [DOC] < 20 mg/L(7), colloid concentration < 0.5 mg/L, low ammonium concentrations, $[Ca^{2+}] + [Mg^{2+}] > 4$ mg/L at repository depth and low concentrations of Rn and Ra. These preferences are set to ensure limited concern as to the effects of organic matter, ensure no colloid enhanced transport, ensure no colloid generation from the buffer and to ensure safe working conditions underground. If concentrations measured during the site investigation deviate adversely from these preferences the safety implications need to be specifically assessed.

### *Additional considerations*

The previously set of criteria relates only to groundwater at repository depth at the present day. It is important to note also that the evolution of the chemical characteristics of groundwater is important for the safety functions and that this will be evaluated in the Safety Assessment.

The SR-Can Interim report /SKB 2004a/ states that the total concentration of divalent cations should exceed 1 mM, i.e. around 40 mg/L, in order to avoid chemical erosion of buffer and backfill. This is a stricter condition than the one mentioned above. Also, it should be noted that SR-Can intends to carry out a detailed evaluation of the different potential backfill materials and how they would be affected by different salinity levels.

Furthermore, the redox buffering capacity of the geosphere may be evaluated from detailed mineralogical evaluations of the rock types found in the Laxemar subarea (see Chapter 5 of SDM L1.2 for a detailed listing of the rock types), as well as of the fracture-filling minerals. The redox-related parameters of interest are Fe(II) and sulphide content. The redox buffering capacity is of importance when evaluating the impact of the operational phase. In case of a glaciation, the effects of introducing glacial melt water, that may be oxygen-rich, would also depend on the redox buffering. Similarly, the pH-buffering capacity may also be evaluated from the amounts of calcite in the fractures. Detailed mineralogical data were not available for the SDM L1.2, and therefore this aspect of the site geochemistry cannot be evaluated at this stage.

## 3.6.2 Current groundwater composition

According to the conceptual hydrogeochemical model of SDM L1.2, see Figure 3-19, the complex groundwater evolution and patterns at the Laxemar subarea are a result of many factors such as: a) the present-day topography and proximity to the Baltic Sea, b) past changes in hydrogeology related to glaciation/deglaciation, land uplift and repeated marine/lake water regressions/transgressions, and c) organic or inorganic modification of the groundwater composition caused by microbial processes and water/rock interactions. The sampled groundwaters reflect to various degrees processes relating to modern or ancient water/rock interactions and mixing.

According to the model, see Figure 3-19, four main groundwater types, Types A, B, C and D, are present.

- A: Shallow (< 200 m) at Simpevarp but deeper (down to ~ 800 m) at the Laxemar subarea. Dilute groundwater (< 2,000 mg/L Cl; 0.5–3.5 g/L TDS); $\delta^{18}O = -11$ to $-8$‰ SMOW. Mainly meteoric and $Na\text{-}HCO_3$ in type. Redox: Marginally oxidising close to

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[7] In /Andersson et al. 2000/ it was only stated that DOC concentrations at depth should be low, the value of 20 mg/L has later been decided to be a reasonable preferred upper limit. /Andersson et al. 2000/ also suggested that [DOC] > 10 mg/L in surface waters.

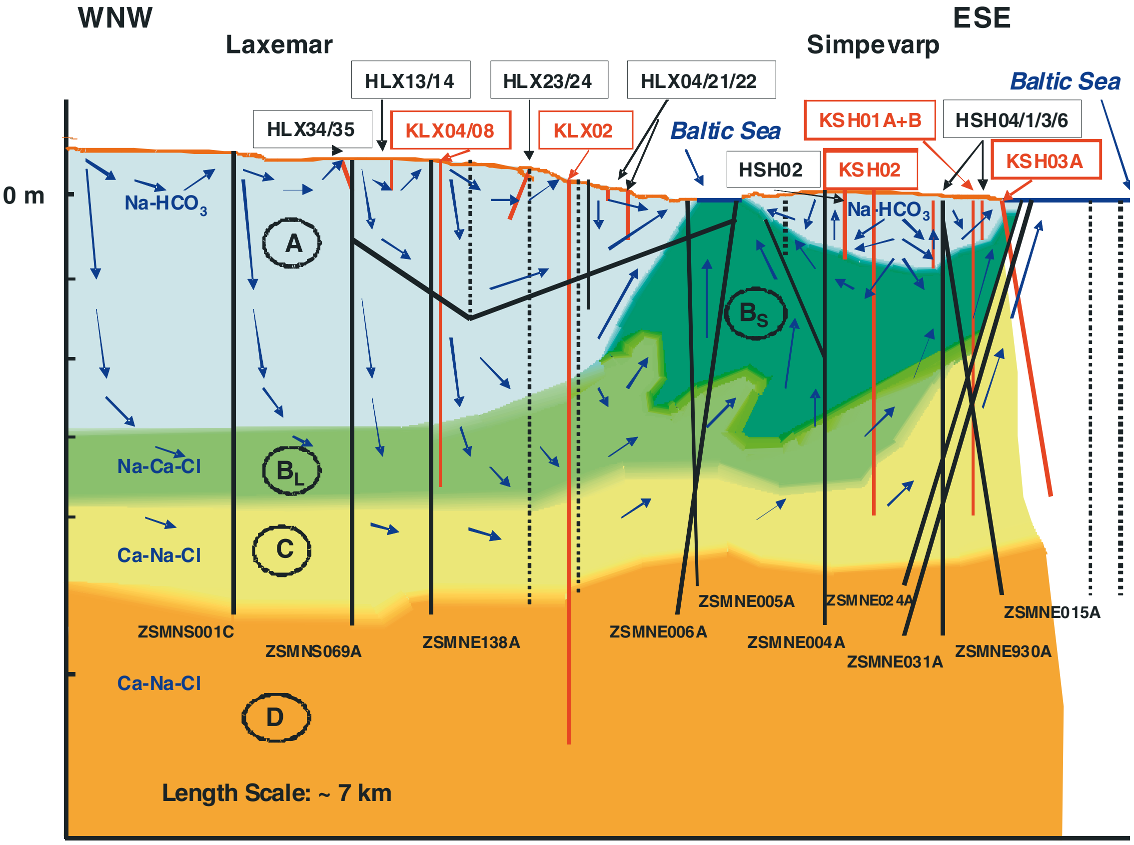

***Figure 3-19.*** *Schematic 2-D visualisation along the WNW-ESE transect and to about 2 km depth, integrating the major structures, the major groundwater flow directions and the variation in groundwater chemistry from the sampled boreholes. Sampled borehole sections are indicated in red, major structures are indicated in black (full lines = confident; dashed lines = less confident), and the major groundwater types A–D are also indicated. The blue arrows are estimated groundwater flow directions. (From SDM L1.2).*

the surface, otherwise reducing. Main reactions: Weathering; ion exchange (Ca, Mg); dissolution/precipitation of calcite; redox reactions (e.g. precipitation of Fe-oxyhydroxides); microbially-mediated reactions (SRB) which may lead to formation of pyrite. Mixing processes: Mainly meteoric recharge water at the Laxemar subarea; potential mixing of recharge meteoric water and a modern sea component at Simpevarp subarea; localised mixing of meteoric water with deeper saline groundwaters at Laxemar and Simpevarp subareas.

- B: Shallow to intermediate (150–600 m) at Simpevarp but deeper (down to ~ 500–950 m) at the Laxemar subarea: Brackish groundwater (2,000–10,000 mg/L Cl; 3.5–18.5 g/L TDS); $\delta^{18}O$ = –14 to –11‰ SMOW. $B_L$ – Laxemar subarea: Meteoric, mainly Na-Ca-Cl in type; Glacial/Deep saline components. $B_S$ – Simpevarp subarea: Meteoric mainly Na-Ca-Cl in type but some Na-Ca(Mg)-Cl(Br) types (± marine, e.g. Littorina); Glacial/Deep saline components. Redox: Reducing. Main reactions: Ion exchange (Ca, Mg); precipitation of calcite; redox reactions (e.g. precipitation of pyrite) Mixing processes: Potential residual Littorina Sea (old marine) component at Simpevarp, more evident in some fracture zones close to or under the Baltic Sea; potential glacial component at both the Simpevarp and Laxemar subareas; potential deep saline (non-marine) component at both the Simpevarp and at Laxemar subareas.

- C: Intermediate to deep (~600–1,200 m) at Simpevarp but deeper (900–1,200 m) at the Laxemar subarea: Saline (10,000–20,000 mg/L Cl; 18.5–30 g/L TDS); $\delta^{18}O$ = ~ –13‰ SMOW (bit only few data). Dominantly Ca-Na-Cl in type at Laxemar but Na-Ca-Cl changing to Ca-Na-Cl only at the highest salinity levels at the Simpevarp subarea; increasingly enhanced Br/Cl ratio and $SO_4$ content with depth at both the Simpevarp and Laxemar subareas; Glacial/Deep saline mixtures. Redox: Reducing. Main reactions: Ion exchange (Ca). Mixing processes: Potential glacial component at both the Simpevarp and Laxemar subareas; potential deep saline (i.e. non-marine) and an old marine component (Littorina?) at shallower levels at the Simpevarp subarea; Deep saline (non-marine) component at the Laxemar subarea.
- D: Deep (> 1,200 m) only identified at a single borehole in the Laxemar subarea. Highly saline (> 20,000 mg/L Cl; to a maximum of ~70 g/L TDS); $\delta^{18}O$ = > –10‰ SMOW. Dominantly Ca-Na-Cl with higher BrCl ratios and a stable isotope composition that deviates from the GMWL when compared with Type C groundwaters; Deep saline/brine mixture; Diffusion dominant transport process. Redox: Reducing. Main reactions: Water/rock reactions under long residence times Mixing processes: Probably long term mixing of deeper, non-marine saline component driven by diffusion.

Compared with the Simpevarp 1.2 subarea version of the hydrogeochemistry /SKB 2004e, 2005c/ one of the major differences is the extent of the brackish 'B' type groundwaters, especially in the Simpevarp subarea. This is in part due to the absence of borehole KLX01, omitted because: a) it is located too far from the transects to be satisfactorily projected, and b) it has a marine component which makes it more representative for the NE 'close to the Baltic Sea' part of the Laxemar subarea but anomalous in the 'total' Laxemar subarea context. The 'B' type groundwaters in the Laxemar subarea therefore become meteoric and brackish, containing a mixture of glacial/deep saline groundwaters but devoid of an old marine (i.e. Littorina) component. They are referred to as '$B_L$' type groundwaters. In the Simpevarp subarea the 'B' type groundwaters differ in that there is a weak but significant component of Littorina present, and these are referred to as '$B_S$' type groundwaters. As indicated in Figure 3-19 the $B_L$ groundwaters are continuously moving into the Simpevarp subarea at depth, mixing with the $B_S$ groundwaters and gradually discharging to shallower levels.

The conceptual hydrogeochemical description is largely consistent with the hydrogeological description. Figure 3-20 shows a simulated distribution of salinity (TDS) along a WNW-ESE cross section using the regional scale hydrogeological model presented by /Hartley et al. 2006/ and briefly discussed in Section 3.5.3. The overall distribution of saline water compares well with Figure 3-19, although the flow simulations tend to overestimate the flushing of the saline water to too greater depths. In fact, by exploring variant cases /Hartley et al. 2006/ note that reducing the fracture transmissivity by half an order of magnitude below the –600 m elevation is sufficient to significantly improve the representation of palaeohydrogeology at depth. This is well within the levels of uncertainty of the hydraulic properties, see Section 3.5.2.

By the time of the data freeze for L1.2, there were no new representative samples from repository depth from the Laxemar subarea. Therefore samples from earlier sampled boreholes were used to check if they met the chemical suitability criteria for Eh, pH, TDS, DOC and Ca+Mg (described in Section 3.6.1). The samples from KLX01:680–702 m (sampled in year 1988) and KLX02:798–803 m (sampled in year 1993) where selected for this purpose despite their reflecting conditions below repository depth, see Table 3-17. The table also shows the limits implied by criteria and other safety considerations (see Section 3.6.1).

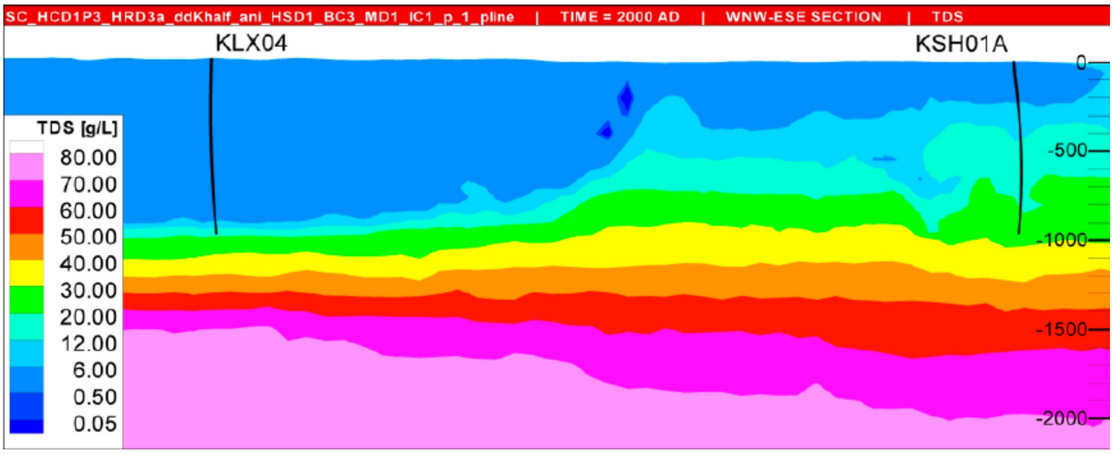

***Figure 3-20.** Simulated distribution of salinity (TDS) along a WNW-ESE cross section using the regional scale hydrogeological model presented by /Hartley et al. 2006, Figure 9-9/. The figure should be compared with the conceptual model of hydrogeochemistry shown in Figure 3-19.*

**Table 3-17. Analysed values of the samples KLX01:680–702 m and KLX02:798–803 m. It should be noted that these samples lie much below potential repository depth (Based on Table 9-3 in SDM L1.2).**

| | Eh (mV) | pH (units) | TDS (g/L) | DOC (mg/L) | Colloids (mg/L) | Ca+Mg (mg/L) |
|---|---|---|---|---|---|---|
| Criterion | < 0 | 6–10 | < 100 | < 20 | < 0.5 | > 40 |
| KLX01: 680–702 m | –275 | 8.1 | 8.2 | 1.2 | 0.03 | 1,423 |
| KLX02: 798–803 m | –125* | 7.6 | 0.9 | 5 | n.a. | 134 |

* Measured during a sampling event in year 2002. Not analysed = n.a.

There are several uncertainties in the hydrogeochemical description as is further discussed in Chapter 12 of SDM L1.2.

The spatial variability of groundwater composition at depth is uncertain. The information density concerning borehole groundwater chemistry is low. The samples are mixed and represent an average composition. There is a lack of data on water composition in the low conductive fractures and in the matrix. The basic model is the interpolated distribution from the data. An alternative hypothesis is that there are lenses of "deviating" groundwater composition (glacial water) in the low conductive fractures and in the matrix. This uncertainty may cause uncertainties concerning the salinity interface in e.g. hydrogeological and transport modelling, and affect the overall hydrogeochemical understanding of the site. The description of the interaction between groundwaters in the highly permeable and low permeable systems will also remain uncertain as long as there are few matrix pore water data.

There are uncertainties related to the important chemical reactions controlling redox and pH. There is inaccuracy in pH measurements, inaccuracy in the thermodynamic databases, potential errors in mineral phase selections and potential errors in end-members selection. Probably, the important chemical reactions that control the redox are known, but the uncertainty is in where the reducing agent (e.g. methane) emanates and how it gets there. Different modelling approaches are applied to the same data set to describe the same processes thereby confidence is built into the description, see SDM L1.2 for details.

Temporal averaging implies uncertainties in the seasonal variability in surface water chemistry, which ultimately impacts the composition of the groundwater in the bedrock. The sampling may not describe the seasonal variation and samples may be taken at different times from the surface than from the shallow boreholes. This can cause uncertainty concerning the interaction between surface and groundwaters and may affect transport modelling. The effects from seasonal variation have not been quantified but have been identified, see SDM L1.2.

### 3.6.3 Safety implications

The previous sections show that the Laxemar subarea meets all hydrogeochemical requirements and preferences.

- Table 3-17 shows that the groundwater composition sampled below potential repository depth in the Simpevarp area lies well within both the required and preferred bounds. However, there are no new representative samples from repository depth from the Laxemar subarea, so a formal check of suitability will be needed once such samples are available. There is however, little reason to believe that these samples would show non-acceptable conditions.
- Furthermore, even if the exact spatial distribution of the water composition is uncertain, essentially all water types conform to the hydrogeochemical criteria. This also means that even if the exact future evolution of groundwater composition is uncertain, due to uncertainties in future groundwater flow, it is highly likely that the groundwater composition will remain, at least for temperate climate conditions, within the range of the required and preferred criteria also in the future.

Overall, it is judged that there is a rather good understanding of the hydrogeochemistry at the site. The consistency between the hydrogeochemical and hydrogeological descriptions lends support to the conceptual model. But there are still uncertainties. Representative data from repository depth at the Laxemar subarea are needed. There is also a lack of data on water composition in the low conductive fractures and in the matrix. This means that even if the hydrogeochemical requirements and preferences are met, further reduction of uncertainties in the spatial distribution at depth is desirable to further improve the understanding of the hydrogeochemistry and thus enhance the safety case. The additional data and evaluations suggested for this in SDM L1.2 are considered appropriate.

As already mentioned, SR-Can also intends to carry out a detailed evaluation of the different potential backfill materials and of how different salinity levels would affect them. This evaluation might also result in further needs for a more detailed evaluation of the present, and a prediction of the future, salinity distribution at the site. Furthermore, in order to have a full evaluation of the redox buffering capacity of the geosphere, more mineralogical data, Fe(II) and sulphide content determinations of the rock and evaluations of the amount of fracture minerals in contact with the flowing water would be needed.

## 3.7 Radionuclide transport

The only pathway by which radionuclides could migrate from breached canisters into the biosphere is through groundwater flow. That migration, and the retardation of the migration, is controlled by the distribution of the groundwater flow and the sorption properties of the rock matrix along the migration paths.

### 3.7.1 Criteria and other safety considerations

#### *Previously set criteria*

The suitability criteria, as set out by SKB in /Andersson et al. 2000/, directly related to the transport properties of the site concern the flow-related transport properties, i.e. groundwater flow (Darcy velocity) at canister scale, transport resistance F, and the migration properties of the rock matrix.

It is *required* that the Darcy velocity at the canister scale and the total fracture aperture are not large enough to damage the bentonite during deposition. However, this can always be controlled and avoided during deposition and is not further discussed here. For safety, there is instead a *preference* for the Darcy velocity, after closure and resaturation, at the canister scale to be less than 0.01 m/y for a large number of positions in the rock, since flows less than this helps in limiting the release of radionuclides from the buffer in case a canister is breached. There is also a *preference* that a large fraction of flow paths from potential canister positions through the rock should have a transport resistance F > $10^4$ y/m, as such high F-values imply significant retention of sorbing radionuclides. However, /Andersson et al. 2000/, also point out that these “limiting” values should be seen as a guideline and that a final judgement of the adequacy of retention is made within the framework of a safety assessment.

Also the migration properties of the rock matrix affect radionuclide retention in the rock. It is a *preference* that matrix diffusivity and matrix porosity are not much lower, i.e. by more than a factor of 100, than the value ranges analyzed in the safety assessment SR 97 (see the SR-97 Data Report /Andersson 1999/). Also, the accessible diffusion depth should at least exceed a centimetre or so. Otherwise, special consideration of the safety implications will be required in forthcoming safety assessments.

#### *Additional considerations*

There are no additional considerations. However, it should be noted that the degree of retention of a radionuclide is element specific and that the importance of the retention depends on the release situation and the half-life of the individual radionuclide. Combining all such aspects is an important part of a safety assessment and will be done in SR-Can, but lies outside the scope of the PSE. This also means that the criteria on migration properties of the rock matrix as well as on Darcy velocity and transport resistance should be seen as guiding indications – not as strict rules.

### 3.7.2 Migration properties of the rock matrix

As further explained in Chapter 10 of SDM L1.2, in the site descriptive modelling of transport properties site specific data have been used to parameterise a retardation model that considers the transport properties (porosity, diffusivity and sorption coefficients) of the major rock domains as well as the properties of type fractures with focus on the Laxemar subarea, see Table 3-18. The retardation model for rock domains considers the properties of the unaltered intact rock matrix under natural stress conditions, whereas that for type fractures considers additionally the material properties of alteration zones of various kinds and extents within the wall rock adjacent to fracture flow paths. No attempt has been made to parameterise local minor and local major deformation zones owing to a lack of hard data for these structures. These, however, are not currently considered to contribute substantially to the overall transport resistance, as transport through them is considered rapid. Site investigation data from porosity measurements and diffusion experiments (in situ and in the laboratory) are available. Furthermore, a major improvement in the current site descriptive model is the inclusion of sorption data for a larger set of nuclides, representing a wider range of sorption properties, than was available for the previous model version.

### Effective diffusivities of major rock types

The diffusivity is quantified through the formation factor, $F_m$, which is related to the diffusivity as $F_m = D_e/D_w$ ($D_w$ is the free diffusivity in water). Formation factors are obtained from through-diffusion experiments and electrical resistivity measurements both in the laboratory and in situ. The resistivity can be measured both in laboratory experiments (where the rock samples are saturated with 1 M NaCl) and in borehole in situ experiments. In contrast, all through-diffusion experiments are made at the laboratory scale.

The effective diffusivity assigned to the various rock types in the retardation model of the Laxemar subarea, is currently based largely upon electrical resistivity measurements carried out in the laboratory. These measurements give effective diffusivities that possibly are up to a factor two larger than those obtained by in situ measurement of electrical resistivity. The differences, however, between in situ and laboratory measurements are not unequivocal when considering the data variance and overall measurement uncertainty. Although in situ measurement data have greater uncertainty due to lack of knowledge concerning the true salinity of matrix porewater, at least part of the difference (if a difference indeed exists) could result from effects of tangential stress concentrations around the borehole paired with effects of stress unloading of rock samples in the case of measurements on core specimens.

Through diffusion measurements made for Ävrö granite using water enriched with tritium give effective diffusivities that are up to two or more orders of magnitude higher than those obtained by electrical resistivity measurements (both laboratory and in situ). It is thought that the higher effective diffusivity of these samples may be due to damage induced during drill core retrieval and sample preparation in combination with stress-induced disturbances, as well as due to experimental artefacts relating to the short drill core samples used for the currently reported through-diffusivity measurements.

It is difficult to give a definitive estimation of relative diffusive properties in the current SDM for Laxemar, as there is a considerable inequality in sample support amongst the different rock types and measurement methods. Based upon the recommended transport parameters in Table 3-18, however, Ävrö granite appears to have the highest effective diffusivity (associated with higher retention) with a formation factor on the order of $F_m > 10^{-4}$. Other reported rock types appear to have essentially similar diffusive properties to each other (formation factors roughly 2–4 times lower than that for Ävrö granite) and any relative differences are speculative owing to the inherent data uncertainty. A particular uncertainty in the current model version is the unknown effective diffusivity of altered Ävrö granite, which is assumed to be representative of all altered rock forms in the Laxemar subarea.

### Sorption properties of major rock types

Table 3-18 also summarises the mean values and standard deviations (expressed as mean value ± one standard deviation) of the properties of the rock mass. Parameter values in italics refer to Kd-values that have not been measured for that particular rock type, but instead have been obtained by extrapolation from the results of the BET[8]-surface area measurements.

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[8] BET is a method for determining the specific surface area of a solid material by use of gas adsorption cf. /Brunauer et al. 1938/.

At present, preliminary sorption measurement data exist only for Ävrö granite taken from a single location in borehole KLX03A. Many of these data are of a provisional nature, owing to the long times required for laboratory characterisation of the samples. The preliminary sorption data are based on a rock-solute contact time of one month for the elements Cs(I), Sr(II), Ni(II), Ra(II), and three months for Am(III). Final sorption measurements will not be made until after six months contact time. Depending on the thickness of the sample, through diffusion experiments also typically require three to six months contact time in order to obtain useful estimates of effective diffusivity using a non-sorbing tracer (tritiated water).

Although there are no laboratory determined sorption measurements for other major rock types available at this time, BET surface area measurements indicate relative sorption strengths for different rock types. However, the order of relative sorption strengths is not the same for different sorbing species. It should be noted that the differences between the rock types are typically very small and, based upon the presently available BET data, are often less than the estimated uncertainty in the sorption data. The proposed order of sorption strengths for different rock types should therefore be treated with utmost caution.

Although there is much uncertainty in establishing a relative order of sorption strengths amongst the various rock types, it is clear that most solutes sorb more strongly under non-saline conditions than under saline conditions. The main exception is Am(III) which appears to be unaffected by different groundwater salinities. From the recommended data, Cs(I) appears to exhibit the smallest dependency upon salinity with only a very modest increase in sorption strength (a factor of roughly < 2) for $K_d$ in non-saline groundwater relative to saline groundwater. For the other solutes, Sr(II) exhibits the largest increase (a factor of roughly 10–100), whereas Ni(II) and Ra(II) show more modest increases with factors of 6–12 and 20–35, respectively.

As further discussed in SDM L1.2, there is uncertainty in matrix retention properties, due to the spatial variability, the limited data set and the lack of site-specific sorption data. Especially the reported values for Am(III) are out of range compared to values obtained in most other studies and the site data needs to be treated cautiously. There is also the question of the potential impact of stress release on core samples. Uncertainties relating to the conceptual model of sorption need also be addressed.

A complicating factor in the present analysis is the potential systematic differences obtained between the in situ formation factor measurements and the corresponding laboratory measured formation factors. Both methods involve methodological uncertainties; for the in situ measurements there is only very limited information concerning the pore liquid composition, whereas the laboratory samples show indications of having been exposed to stress release. Nevertheless, the differences in resulting formation factors (in the order of a factor of two) is quite small in relation to the sensitivity of this parameter to retention.

The porosity measurements indicate a large spread in data, even for samples taken very close to each other. In forthcoming site descriptions, it is foreseen that results from porosity measurements with alternative methods will be available, thus enabling sample heterogeneity to be addressed. It is also foreseen that a better description of site-specific sorption properties will be available in forthcoming site descriptions of Laxemar.

The uncertainty is quantified as a range of properties, as indicated in Table 3-18.

**Table 3-18. Suggested transport parameters for the major rock types in the Laxemar subarea. Values are given as mean ±σ for the considered data set where available. Parameter values in italics refer to Kd-values that have not been measured for that particular rock type, but instead have been obtained by extrapolation from the results for the BETsurface area measurements. (Table 10-4 of SDM L1.2).**

| Rock Type | Porosity (vol%) | Formation factor (–) | Water type | Kd ($m^3$/kg) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Cs(I) | Sr(II) | Ni(II) | Ra(II) | Am(III) |
| Ävrö granite | 0.27 ± 0.09 | $(1.4 \pm 1.0)\cdot10^{-4}$ | III | $< 2\cdot10^{-2}$ | $< 4\cdot10^{-4}$ | $(1.1 \pm 0.6)\cdot10^{-2}$ | $(4.0 \pm 3.6)\cdot10^{-3}$ | $(1.0 \pm 0.5)\cdot10^{-2}$ |
| | | | I | $(4.2 \pm 3.5)\cdot10^{-2}$ | $(5.8 \pm 1.4)\cdot10^{-3}$ | $(1.3 \pm 0.8)\cdot10^{-1}$ | $(1.4 \pm 1.1)\cdot10^{-1}$ | $(1.0 \pm 0.5)\cdot10^{-2}$ |
| Quartz monzodiorite | 0.17 ± 0.08 | $(3.6 \pm 3.5)\cdot10^{-5}$ | III | *$< 9\cdot10^{-2}$* | *$< 4\cdot10^{-5}$* | *$< 1.5\cdot10^{-2}$* | *$< 5\cdot10^{-3}$* | *$< 1.4\cdot10^{-2}$* |
| | | | I | *$< 0.11$* | *$< 4\cdot10^{-3}$* | *$< 0.1$* | *$< 0.1$* | *$< 1.3\cdot10^{-2}$* |
| Fine-grained dioritoid | 0.14 ± 0.14 | $1.0\cdot10^{-5}{}_{A}$ | III | *$(1.0 \pm 0.9)\cdot10^{-1}$* | *$< 10^{-4}$* | *$(1.8 \pm 0.9)\cdot10^{-2}$* | *$(5 \pm 3)\cdot10^{-3}$* | *$(1.7 \pm 1.0)\cdot10^{-2}$* |
| | | | I | *$(1.4 \pm 0.7)\cdot10^{-1}$* | *$(5 \pm 3)\cdot10^{-3}$* | *$(1.2 \pm 0.7)\cdot10^{-1}$* | *$(1.2 \pm 0.6)\cdot10^{-1}$* | *$(1.7 \pm 1.0)\cdot10^{-2}$* |
| Fine-grained diorite-gabbro | 0.22 ± 0.08 | $(6.4 \pm 4.2)\cdot10^{-5}$ | III | *$(1.0 \pm 0.8)\cdot10^{-1}$* | *$< 10^{-4}$* | *$(1.8 \pm 0.6)\cdot10^{-2}$* | *$(5 \pm 2)\cdot10^{-3}$* | *$(1.6 \pm 0.6)\cdot10^{-2}$* |
| | | | I | *$(1.4 \pm 0.4)\cdot10^{-1}$* | *$(5 \pm 2)\cdot10^{-3}$* | *$(1.1 \pm 0.6)\cdot10^{-1}$* | *$(1.1 \pm 0.3)\cdot10^{-1}$* | *$(1.6 \pm 0.5)\cdot10^{-2}$* |
| Fine-grained granite | 0.22 ± 0.0002 | No data | III | No data | No data | No data | No data | No data |
| | | | I | No data | No data | No data | No data | No data |
| Granite | 0.38 | $8.0\cdot10^{-5}{}_{A}$ | III | No data | No data | No data | No data | No data |
| | | | I | No data | No data | No data | No data | No data |
| Diorite to gabbro | No data | No data | III | *$(7 \pm 6)\cdot10^{-2}$* | *$< 6\cdot10^{-5}$* | *$(1.2 \pm 0.3)\cdot10^{-2}$* | *$(3.6 \pm 0.8)\cdot10^{-3}$* | *$(1.1 \pm 0.3)\cdot10^{-2}$* |
| | | | I | *$(9 \pm 2)\cdot10^{-2}$* | *$(3.5 \pm 0.8)\cdot10^{-3}$* | *$(8 \pm 4)\cdot10^{-2}$* | *$(8 \pm 2)\cdot10^{-2}$* | *$(1.1 \pm 0.3)\cdot10^{-2}$* |
| Altered Ävrö granite (selected to represent all altered wall rock) | No data | No data | III | *$(1.4 \pm 1.1)\cdot10^{-1}$* | *$< 10^{-4}$* | *$(2.5 \pm 0.7)\cdot10^{-2}$* | *$(7 \pm 2)\cdot10^{-3}$* | *$(2.2 \pm 0.7)\cdot10^{-2}$* |
| | | | I | *$(1.9 \pm 0.4)\cdot10^{-1}$* | *$(7 \pm 2)\cdot10^{-3}$* | *$(1.6 \pm 0.7)\cdot10^{-1}$* | *$(1.6 \pm 0.4)\cdot10^{-1}$* | *$(2.2 \pm 0.6)\cdot10^{-2}$* |

A: Data is based upon a single measurement therefore no uncertainty interval is given.

### 3.7.3 Flow-related migration parameters

#### *First order evaluation of transport resistance*

Given the complex spatially varying network of migration paths existing at the site and the uncertainties in the hydrogeological DFN model it is necessary to consider the measured information and possible distribution of flow paths in the rock in order to obtain a reasonable low order approximation of the transport resistance. These analyses will supplement the more complex DFN-analyses contemplated for SR-Can.

Generally the transport resistance F along a migration path (channel) can be expressed as (see e.g. /Moreno and Neretnieks 1993/, /Vieno et al. 1992/ or /RETROCK 2005/):

$$F=2WL/Q \qquad (1)$$

where W is the width of the channel, L the migration distance and Q the flow in the channel. If the flow geometry was fully known this formula could be used to calculate the transport resistance for the different flow paths. This is the approach taken when estimating this distribution in DFN migration analyses to be conducted within SR-Can. However, the transport modelling in SDM L1.2 uses a more simplistic approach by exploring the possible ranges resulting from the measured hydraulic data. Given the complexities of the hydrogeological DFN-modelling it is of interest to make such an evaluation without using the DFN results, as this provides a context in which the DFN results can be seen as refining the analysis.

#### *Infinite fractures with constant transmissivity*

Consider a fracture of transmissivity T. The flow over a width W is then given by $Q=W \cdot T \cdot grad(H)$, where grad(H) is the hydraulic gradient. If flow is considered to be evenly distributed in the fracture, the transport resistance is given by:

$$F = 2WL/Q = 2WL/(WTgrad(H)) = 2L/(Tgrad(H)) \qquad (2)$$

i.e. in this case the transport resistance is independent of the width of the migration path. Assuming a gradient of 0.5%, which is certainly higher than found at the site at 500 m depth, and a migration distance of 100 m results in the transport resistances listed in Table 3-19.

**Table 3-19. Transport resistance F for different fracture transmissivities assuming a gradient of 0.005 and 100 m migration length.**

| T ($m^2/s$) | F (s/m) | F (year/m) | log10(F) year/m |
|---|---|---|---|
| $10^{-6}$ | $4 \cdot 10^{10}$ | $1.3 \cdot 10^{3}$ | 3.1 |
| $10^{-7}$ | $4 \cdot 10^{11}$ | $1.3 \cdot 10^{4}$ | 4.1 |
| $10^{-8}$ | $4 \cdot 10^{12}$ | $1.3 \cdot 10^{5}$ | 5.1 |
| $10^{-9}$ | $4 \cdot 10^{13}$ | $1.3 \cdot 10^{6}$ | 6.1 |
| $10^{-10}$ | $4 \cdot 10^{14}$ | $1.3 \cdot 10^{7}$ | 7.1 |

### *Estimations of the F-factor and its distribution using site specific data for Laxemar*

By various approaches, building upon the main observations made above, SDM L1.2 provides estimations of the F-factor and its distribution using site specific data for Laxemar. It is noted that assessing a realistic site specific value for the transport resistance is dependent upon correctly predicting the transmissivities, extents, frequencies, and connectivity of conductive features in the rock volume being investigated. It is clear from borehole hydraulic tests that there is a broad distribution of flow rates and transmissivities that characterise different flowing features. Furthermore, the F-factor is dependent not only on the hydraulic characteristics of individual flowing features comprising a flow path, but also their interconnectivity in the extended network of fractures surrounding the repository. Radionuclides may be transported over a number of independent flowpaths. The effective F-factor for such an ensemble of possible flow paths therefore is best described in terms of a statistical distribution of F-factors.

Although the network of flow channels and potential migrations paths is complex, it is possible to make estimates of the F-factor distribution from site-specific data according to different conceptual models that represent extremes of possible behaviour. While not altogether physically realistic, they nonetheless can provide approximate bounds for the likely distribution of transport resistance to be found in the repository target volume. Moreover, they can also be used to provide a “reality check” on more sophisticated models where underlying concepts and assumptions may not be as transparent.

Two different conceptual models are used to make estimates of the mean F-factor and its distribution. These are the Channel Network Model (CNM) /Moreno and Neretnieks 1993, Gylling 1997/ and the Stochastic Multi Channel Model (MCM) /Neretnieks 2002/. These models represent extremes of flow channel interconnectivity and are described in some detail in the background report by /Crawford 2006/. Simulations have been made with both model concepts to evaluate the transport resistance distribution of the rock surrounding the repository:

- In the CNM concept, it is assumed that fluid flow and solute transport take place in a network of interconnected flow channels. The channels within the network are short and highly interconnected, with transmissivities sampled randomly from a lognormal distribution. Using a particle tracking technique, the F-factor distribution for an ensemble of transport paths can be calculated for different flow network realisations.
- The MCM concept is essentially an extension of the first-order approximation discussed at the beginning of this section. In this case, however, solutes are assumed to be released simultaneously within a cluster of independent non-mixing flow channels. It may also be noted that the MCM model would more emphasise transport in the longer more transmissive fractures in a DFN model with a power law distribution of fracture lengths and a transmissivity that increases with length. The individual flow channels have transmissivities reflecting the measured transmissivity distribution obtained from borehole data. This is the same as estimating the F-factor using Equation (2), although extending the calculation to the entire transmissivity distribution.

If the measured transmissivity distribution is assumed to be representative of individual flow channels, then the magnitude of the F-factor calculated using either the CNM or MCM approaches can be shown to be formally insensitive to flow channel width for any specified channel length. Owing to the short and highly interconnected nature of the flowpaths in the CNM, the calculated F-factor distribution tends to reflect the average flow properties of channel members making up the flowpath ensemble within the rock volume. The variance of the F-factor distribution is, therefore, dependent upon the number of channels and mixing nodes separating the release and recovery locations. This is contingent upon the choice of channel length, although this can be considered to be a secondary effect of flow path discretisation. To illustrate the impact of different assumptions of average channel length, CNM simulations have been made using a range of channel lengths between 1–10 m. It should be noted that the CNM and MCM approaches have, on average, the same "flow wetted surface" per volume of rock. The difference between the concepts is that in the CNM description each migration path would sample different flows making all flow paths approaching an average of the different flows, whereas different flow paths in the MCM description will have very different flows.

Estimated site-specific F-factor data, calculated using both the CNM and MCM approaches, are given in Table 3-20 below for a nominal path length of 100 m and a representative hydraulic gradient of 0.5%. The mean F-factor calculated using the CNM is slightly higher than that calculated using the MCM approach, but values are relatively similar. However, a significant difference between calculations made with the CNM and MCM approaches is the magnitude of the estimated variance for the F-factor distribution and consequently, also the calculated 10 and 1 percentile values. The variance of the F-factor calculated using the CNM is reduced considerably by the interconnectedness of the channel network whereas the MCM model has an F-factor variance that is identical to that of the original transmissivity distribution. The 10 percentile and 1 percentile correspond to the F-factors where at most 10 percent and 1 percent, respectively, of flow channels have a lower F-factor (assuming a lognormal distribution).

These findings could also be compared with the hydraulic data listed in Table 3-14 and the F-values of Table 3-19. The highest transmissivity encountered below –300 m in KLX03 is about $5\cdot10^{-7}$ in KLX03, which corresponds to a logF below 4, and the highest transmissivity encountered below –300 m in KLX04 is about $2\cdot10^{-6}$ m$^2$/s, which corresponds to a log F just below 3. These results are consistent with findings in Table 3-20.

It should be remembered that the actual F-factor distribution for a given radionuclide release scenario is strongly dependent upon the connectivity of flowpaths leading from the deposition hole through the immediate far-field and is particularly sensitive to the number and transmissivity of the fractures initially encountered in the vicinity of a leaking canister. The "actual" F-factor for transport from a leaking canister is therefore subject to a large degree of variation depending upon the probability of channels with various transmissivities intersecting a deposition hole and their connectivity with the wider fracture network.

### *Results from regional flow simulations*

As already discussed in Section 3.5.3, /Hartley et al. 2006/ have calculated flow paths in the regional-scale, equivalent porous medium hydrogeological model, from release areas approximately located within the Laxemar subarea at 500 m depth. The groundwater model is transient and includes density dependent flow, but the flow paths are only assessed for the velocity field simulated for the present day. The particles were released within a rectangle and with a spacing of 50 m, see Figure 3-16. As a separate effort, and not reported in the SDM L1.2, /Hartley et al. 2006/ also calculated advective travel time ($t_w$), canister flux ($q_c$, Darcy velocity), F-value (F) and path length (L) for each of these flow paths.

**Table 3-20. Estimated F-factor using site-specific data for various boreholes in the Laxemar subarea. Data were evaluated using a Channel Network Model (CNM) considering a range of possible channel lengths ($L_c$) and a Multi Channel Model (MCM). Both models consider an overall nominal path length of 100 m and a hydraulic gradient of 0.5% /from Crawford 2006/.**

| Borehole ID | Test Type | Test Scale (m) | Log10(Tm) ($m^2$/s) | Lc (m) | Model | $Log_{10}(F_m)$ (y/m) | $Log_{10}(F_{U10\%})$ (y/m) | $Log_{10}(F_{U1\%})$ (y/m) |
|---|---|---|---|---|---|---|---|---|
| KLX02 | PFL-s | 3 | –9.32 ± 1.27 | 1 | CNM | 6.86 ± 0.16 | 6.67 | 6.51 |
| | | | | 2 | CNM | 6.84 ± 0.19 | 6.61 | 6.42 |
| | | | | 5 | CNM | 6.80 ± 0.25 | 6.50 | 6.25 |
| | | | | 10 | CNM | 6.77 ± 0.32 | 6.39 | 6.07 |
| | | | | 100 | MCM | 6.42 ± 1.27 | 4.92 | 3.64 |
| | PSS | 5 | –10.5 ± 2.50 | 1 | CNM | 7.94 ± 0.30 | 7.59 | 7.29 |
| | | | | 2 | CNM | 7.90 ± 0.31 | 7.53 | 7.21 |
| | | | | 5 | CNM | 7.84 ± 0.40 | 7.37 | 6.96 |
| | | | | 10 | CNM | 7.78 ± 0.48 | 7.21 | 6.73 |
| | | | | 100 | MCM | 7.60 ± 2.50 | 4.64 | 2.13 |
| KLX03 | PFL-s | 5 | –10.5 ± 2.19 | 1 | CNM | 7.97 ± 0.27 | 7.65 | 7.38 |
| | | | | 2 | CNM | 7.93 ± 0.30 | 7.57 | 7.27 |
| | | | | 5 | CNM | 7.87 ± 0.39 | 7.42 | 7.03 |
| | | | | 10 | CNM | 7.82 ± 0.46 | 7.28 | 6.82 |
| | | | | 100 | MCM | 7.60 ± 2.19 | 5.01 | 2.81 |
| KLX04 | PFL-s | 5 | –8.5 ± 1.62 | 1 | CNM | 6.01 ± 0.20 | 5.78 | 5.57 |
| | | | | 2 | CNM | 5.99 ± 0.24 | 5.71 | 5.46 |
| | | | | 5 | CNM | 5.94 ± 0.31 | 5.57 | 5.26 |
| | | | | 10 | CNM | 5.90 ± 0.38 | 5.45 | 5.07 |
| | | | | 100 | MCM | 5.60 ± 1.62 | 3.68 | 2.05 |
| | PSS | 5 | –8.5 ± 2.00 | 1 | CNM | 5.98 ± 0.25 | 5.69 | 5.44 |
| | | | | 2 | CNM | 5.95 ± 0.29 | 5.61 | 5.32 |
| | | | | 5 | CNM | 5.90 ± 0.37 | 5.46 | 5.10 |
| | | | | 10 | CNM | 5.84 ± 0.43 | 5.33 | 4.89 |
| | | | | 100 | MCM | 5.60 ± 2.00 | 3.23 | 1.22 |
| KAV04A | PFL-s | 5 | –8.5 ± 1.33 | 1 | CNM | 6.03 ± 0.16 | 5.84 | 5.68 |
| | | | | 2 | CNM | 6.02 ± 0.20 | 5.78 | 5.58 |
| | | | | 5 | CNM | 5.98 ± 0.26 | 5.66 | 5.40 |
| | | | | 10 | CNM | 5.94 ± 0.33 | 5.55 | 5.22 |
| | | | | 100 | MCM | 5.60 ± 1.33 | 4.03 | 2.69 |

In the SR-Can assessment, the Darcy velocity at canister scale and the transport resistance, F, will be calculated from a nested DFN and Equivalent Porous Medium (EPM) flow simulations, where the repository region is described as a DFN at the detailed scale, as outlined in the SR-Can Interim Report /SKB 2004a, Chapter 9/. However, this procedure is not possible for the large-scale relatively low resolution analyses carried out in the regional flow modelling. The calculated Darcy velocity will be an average for a larger volume and an effective value of the fracture surface area per unit volume of rock, $a_r$, is needed in order to assess the transport resistance.

Conceptually, $a_r$ equals the fracture surface area (both faces of the fracture plane) of the hydraulically connected network per unit volume of rock or twice $P_{32c}$. In a reference case defined by /Hartley et al. 2006/, $a_r$ was given values in the range 0.1–0.5 $m^{-1}$ in the rock mass below –300 m and about 1 $m^{-1}$ in the upper layers of the rock. It should be noted that $a_r$ is highly uncertain and varies with space within a range at least between 0.1 and 1.3 as noted in the transport analyses (see Table 10-9 of SDM L1.2).

Table 3-21 provides a statistical summary of the calculated performance measures for the reference case of /Hartley et al. 2006/. Despite the differences in approach it should be noted that the calculated range of F-factors lies between the extremes given by Table 3-20. Furthermore the mean value of F is rather similar. /Hartley et al. 2006/ also assessed some variants. However, the conclusions of these are relatively trivial and are not repeated here.

As already noted there are several uncertainties related to these results. One important uncertainty is the impact of the averaging resulting from the porous medium description. A more complete set of analyses, and based on the more appropriate DFN-representation at the repository scale will be made in SR-Can. It needs also be remembered that the analysis is based on data that do not fully represent the potential repository volume of the Laxemar subarea. All these uncertainties need to be handled in the full Safety Analysis and the already planned detailed-scale DFN-approach for SR-Can will partly resolve some of these issues, but further assessment is likely to be needed.

### *Overall remarks*

The distribution of transport resistance (F) on Safety Assessment timescales is uncertain. As a derived parameter, the estimation of F and its distribution are strongly influenced both by uncertainties in models used to interpret primary borehole data (i.e., to give transmissivity distributions from PFL and other hydrological investigations) as well as models used to estimate the derived parameter itself (F). This also includes assumptions, both stated and implicit, used in data derivation (e.g., flow dimension and flow geometry). Transmissivity distributions must be on the resolution of individual water conductors to be reliable for F distribution estimations. The uncertainty is partly assessed by scoping calculations to establish an envelope of possible behaviour using a channel network representation. Estimates are, however, model dependent and can vary between alternative model concepts.

**Table 3-21. Statistical summary of the calculated performance measures $t_w$, canister flux $q_c$, F-value and path length L for each of these for the Laxemar release area for the reference case. (Table D-3 of /Hartley et al. 2006/).**

| Statistical entity | $Log_{10}$(tw) | $Log_{10}$(qc) | $Log_{10}$(F) | $Log_{10}$(L) |
|---|---|---|---|---|
| Mean | 2.923 | –2.639 | 5.691 | 3.361 |
| Median | 2.806 | –2.513 | 5.497 | 3.246 |
| 5th percentile | 1.487 | –4.476 | 4.493 | 2.861 |
| 25th percentile | 2.111 | –3.141 | 4.975 | 3.062 |
| 75th percentile | 3.635 | –1.974 | 6.260 | 3.639 |
| 95th percentile | 4.803 | –1.306 | 7.454 | 4.171 |
| Std dev | 1.024 | 0.976 | 0.986 | 0.393 |
| Variance | 1.049 | 0.953 | 0.973 | 0.155 |
| Skewness | 0.387 | –0.951 | 1.312 | 0.722 |
| Kurtosis | –0.536 | 1.393 | 2.848 | –0.449 |
| Min value | 0.406 | –6.364 | 3.686 | 2.748 |
| Max value | 6.102 | –0.446 | 10.500 | 4.396 |

Despite these difficulties, it is still possible to provide bounding estimates of the variability of the F-factor for individual migration paths. The data in Table 3-20 suggests a mean value on the order of about $10^6$ (y/m), but based on the extreme assumptions of channel length and flow channel interdependence investigated, up to 10% of the migration paths could have an F-factor less than $10^4$ (y/m). These observations are consistent with the results of the regional scale migration analysis, Table 3-21. However, it should be noted that, for safety assessment, the relevant issue is the spatial distribution of migration paths related to the scale of individual deposition holes.

The percentile of deposition holes with a low F-factor would not exactly equal the percentile of individual flow paths with this low F-factor in the rock volume as a whole, as a deposition hole could be intersected by a varying number of migration paths (varying from zero to several for each hole). Moreover, the F-factor for a deposition hole would be dominated by the path with lowest F-factor value intersecting the hole. (Another reason that would increase the F-factor in practice is that deposition holes with high inflows and, therefore, likely high outflows may not be used.) Therefore, upscaling using various assumptions in the DFN-model is needed to provide more quantified uncertainty ranges for application within Safety Assessment. Such upscaling will be performed as part of SR-Can. Furthermore, it needs also be remembered that the analysis is based on data that do not fully represent the potential repository volume of the Laxemar subarea, as already noted in Section 3.5.

### 3.7.4 Safety implications

There are no specific requirements on the transport properties other than that they should be sufficient to provide overall safety. Such an overall requirement would likely be fulfilled by meeting the preferences. In fact, the previous sections show that a repository placed at 500 m depth or deeper in the Laxemar subarea, appear to meet stated preferences on transport properties.

- The statistical summary in Table 3-21 shows that more than 75 percent of all starting positions have a calculated Darcy velocity below 0.01 m/yr. The result is little affected by the different variant cases explored.
- It is possible to provide bounding estimates of the variability of the F-factor for individual migration paths. Table 3-20 suggests a mean value on the order of about $10^6$ (y/m), but based on the extreme assumptions of channel length and flow channel interdependence investigated, up to 10% of the migration paths could have an F-factor less than $10^4$ (y/m). However, the percentile of deposition holes with a low F-factor would not exactly equal the percentile of individual flow paths with this low F-factor in the rock volume as a whole, as a deposition hole could be intersected by a varying number of migration paths (varying from zero to several for each hole). Therefore, upscaling using various assumptions in the DFN-model is needed to provide more quantified uncertainty ranges for application within Safety Assessment. Such upscaling will be performed as part of SR-Can.
- Channelling within the fracture could possibly further reduce the F-factor, but not necessarily, see /Rasmuson and Neretnieks 1986/. If the transmissivity data already reflect the channels rather than averages of fracture planes further reduction due to channelling is not needed and if channels are approaching circular holes radial diffusion will partly compensate for the decrease in surface area in the hole. Consideration of channelling within fractures will be made in SR-Can.

- The ranges of porosity and formation factors for the major rock types in the Laxemar surbarea Table 3-18, are within the ranges considered in SR-97, although the Formation Factor (which could be as low as $1 \cdot 10^{-5}$) is at the lower end of the range considered. The SR-97 Data Report /Anderssson 1999/ suggested a matrix porosity between $5 \cdot 10^{-3}$ and $5 \cdot 10^{-4}$, and a Formation Factor of $4.2 \cdot 10^{-5}$.
- The estimated sorption properties, see Table 3-18, are essentially within the range of values considered for SR 97, apart from Ra(II) under saline conditions for which the SR-97 Data Report /Anderssson 1999/ suggested a Kd range of (0.01–0.1) $m^3$/kg, to be compared with 0.004 $m^3$/kg in Table 3-18 and for Am(III), where the SR-97 Data Report suggested a Kd range of 1–5 $m^3$/kg to be compared with 0.01 $m^3$/kg in Table 3-18. These differences, however, do not depend on site-specific differences compared with the SR-97 sites. Especially the reported values for Am(III) are out of range compared to values obtained in most other studies and the site data needs to be treated cautiously. However, if the data are right, the results may carry over to other trivalent actinides. The implied reduction of the retention of these nuclides is still rather small. Nevertheless, the uncertainty in the sorption properties and its impact of radionuclide transport need careful assessment in SR-Can.

In general, the main uncertainties identified in the Laxemar 1.2 modelling are related to the absence of site-specific transport data for both the retardation model and the integrated transport properties model incorporating estimations of the F-factor. The available data are currently insufficient for establishing quantitative relations between transport parameters and other properties such as lengths, orientations and hydraulic properties of fractures and deformation zones.

The estimates of the transport resistance entail many uncertainties, and this will call for a careful analysis within SR-Can and in the following phases of the Site Investigations. More boreholes and subsequent assessment of the data will be needed to determine better bounds on the transport resistance. It needs to be remembered that the analysis in SDM L1.2 is based on data that do not fully represent the potential repository volume of the Laxemar subarea, as already noted in Section 3.5. There is a need to reduce this uncertainty in the site description. Also, reducing the other uncertainties in the hydrogeological DFN-model is needed in order to narrow the bounds given by the first order evaluation provided in SDM L1.2. The data needs identified in Section 3.5.4 are relevant for this purpose as well.

With regard to the migration properties of the rock, it should also be noted that the retention of a radionuclide is element specific and the importance of the retention depends on the release situation and the half-life of the individual radionuclide. Furthermore, the site-specific information on the migration properties of the rock needs to be complemented by more generic data, and it needs to be considered how they are affected by the conceptual uncertainties in the migration processes. Combining site specific and generic data in the presence of conceptual uncertainties is an important part of a safety assessment and will be done in SR-Can, but lies outside the scope of the PSE.

Nevertheless, existing data on the migration properties of the rock do not suggest any strong spatial variation or strong correlation between rock type and migration properties. The uncertainties are more of a conceptual nature, as will be further assessed within SR-Can. More in situ data on the migration properties of the rock would enhance the safety case. Better feedback on this issue will be available in relation to the full migration analysis made within SR-Can.

## 3.8 Importance of analyses previously foreseen but now omitted from the PSE

In the planning document for the PSE, it was envisaged that there would be some analyses in addition to the ones already presented in the previous sections. These analyses were designed to provide further feedback to the continued investigations and site-specific repository design. However, omitting these analyses is judged to have negligible impact on the PSE and for the Laxemar subarea they will be carried out within the further design work and within the Safety Assessment SR-Can. These additional analyses are briefly outlined below.

### 3.8.1 Drawdown and upconing

Drawdown of surface water and upconing of very saline water were not considered in the previously set criteria /Andersson et al. 2000/. However, these processes could change the groundwater composition at the repository level and could thus be of importance for safety. The extent of these disturbances depends to a large extent on the amount of grouting undertaken in order to control the inflow to the facility.

Analyses of drawdown and upconing were envisaged in the PSE planning document, but for practical reasons are not reported here. These analyses are part of the final design analyses (Step F) and the results will be reported there. The long-term implications will be assessed within SR-Can.

### 3.8.2 Influence of grouting and construction materials

The PSE planning report stated that SR-Site will assess the consequence of grouting and other materials, as estimated by Repository Engineering, in the repository, but also envisaged some initial discussion within the PSE. Estimates of the amounts and types will be made as part of the design work, and evaluations for preliminary values would be of little interest. SR-Can will assess the consequences of the occurrence of these materials.

### 3.8.3 Transmission calculations and transport modelling

Probabilistic integrated radionuclide transport and dose calculations will be carried out in the full safety assessment SR-Can. Such modelling efforts are not included in this PSE, essentially since the results cannot be evaluated without a detailed discussion of input data relating not only to the geosphere but also to system components that are not evaluated within the PSE, e.g. the fuel, the canister, the buffer and the deposition tunnels and the backfill.

### 3.8.4 Near-surface hydrology

In the PSE planning document, it was envisaged that the PSE would explore the properties of the near-surface hydrology as provided in the Site Description, but no additional modelling was planned. It was suggested that combining results of the hydrogeological analyses of the discharge point distribution, see Section 3.5.3, with the current understanding of the near-surface hydrology would provide important feedback to the subsequent characterisation work.

Since the issue of the PSE planning report, SKB has decided to publish a surface system model description of each site. The surface system description model for the Laxemar subarea is provided in /Lindborg 2006/. That report provides sufficient feedback on the needs for further characterisation, and additional analyses in the PSE are, therefore, unnecessary.

# 4 Conclusions and recommendations

The main objectives of this Preliminary Safety Evaluation of the Laxemar subarea have been (Section 1.1):

- to determine whether the feasibility study's judgement of the suitability of the candidate area with respect to long-term safety holds up in the light of the site investigation data,
- to provide feedback to continued site investigations and site-specific repository design, and
- to identify site-specific scenarios and geoscientific issues for further analyses.

The fulfilment of these objectives is discussed in the following.

## 4.1 Overall findings regarding long-term safety

The evaluation in the previous chapter shows that according to existing data the Laxemar area *meets all safety requirements* set out by SKB in /Andersson et al. 2000/. In respect of the individual requirements, the following conclusions have been made.

- It is well established that the subarea does not have any ore potential or other potentially valuable resources. The rock type distribution represents typical crystalline basement rock and the remaining uncertainties are of little concern for safety.
- It is clearly possible to locate a sufficiently large repository within the Laxemar subarea while meeting the required respect distances to the deformation zones and assuming a low degree of utilisation. There is considerable reserve space. However, it is also noted that there is considerable uncertainty in the character and geometry of the deformation zones in the area, which means that the current layout of step D1 would likely need to be substantially altered when a less uncertain description is available.
- The calculated proportion of potential canister positions being intersected by discriminating fractures of radius larger than 75 m is in the order of a few percent. This proportion of potentially unsuitable deposition holes is much less than what is assumed in the layout when assessing the degree of utilisation. Uncertainties in the DFN description of the fracture statistics need to be quantified and preferably reduced through further investigations and data evaluations.
- A repository can be constructed, at least down to –500 m, without expecting problems with extensive spalling or rock fallout. In Stress Domain II spalling in the deposition holes is not expected regardless of repository depth. In Stress Domain I the risk of spalling in the deposition holes increases below a repository depth of 450 m. This means that there will be some likelihood of spalling in deposition holes at 500 m. However, the volume change may be so small that few, if any, deposition holes would need to be discarded for this reason. No spalling is expected in the deposition tunnels in stress Domain II at any depth or orientation. However, in Stress Domain I, deposition tunnels oriented perpendicular to the maximum horizontal stress will likely experience minor spalling below 500 m depth.

- It is possible to define a layout that ensures that the required temperature conditions on the buffer are fulfilled. The recently relaxed thermal requirement puts a limit on the maximum temperature in the buffer at 100°C but with no requirement on the canister temperature. The current repository layout has a considerable margin to the 100°C criterion for the peak buffer temperature. In fact, even a canister spacing of 6 m would possibly be sufficient for fulfilling the thermal requirement on the buffer.
- The groundwater composition sampled below potential repository depth in the Simpevarp area lie well within both the required and preferred bounds. However, there are no new representative samples from repository depth from the Laxemar subarea so a formal check of suitability will be needed once such samples are available. There is, however, little reason to believe that these samples would show unacceptable conditions.

The evaluation also shows that the Laxemar subarea *meets most of the safety preferences*, but for some aspects of the site description further reduction of the uncertainties would enhance the safety case. More detailed conclusions are given below.

- The uniaxial compressive strength is comparatively low compared with the more elevated stress levels found in Stress Domain I. Furthermore, there is a lack of representative data from all important rock types in the potential repository volume.
- In the current hydrogeological model more than 75 percent of the blocks with the 20 m scale in HRD(D,E,M) have hydraulic conductivity below $10^{-8}$ m/s and in HRD(A) only a little more than 50 percent of the blocks at the 20 m scale have hydraulic conductivity below $10^{-8}$ m/s. This means that there could be some uncertainty whether the preference on low hydraulic conductivity is met. The uncertainties are also rather large primarily due to the potentially poor representativity of the data. The spatial distribution of the hydraulic properties is still not sufficiently determined and the uncertainties in that spatial distribution and in the magnitude of the parameters characterising those properties need to be reduced.
- It is possible to provide bounding estimates of the variability of the F-factor for individual migration paths. With extreme assumptions of channel length and flow channel interdependence, up to 10% of the migration paths could have an F-factor less than $10^4$ (y/m). However, the percentage of deposition holes with a low F-factor would not exactly equal the percentage of individual flow paths with this low F-factor in the rock volume as a whole, as a deposition hole could be intersected by a number of migration paths (varying from zero to several for each hole). Therefore, upscaling using various assumptions in the DFN-model is needed to provide more quantified uncertainty ranges for application within Safety Assessment. Such upscaling will be performed as part of SR-Can. It needs also be remembered that the analysis is based on data that do not fully represent the potential repository volume of the Laxemar subarea, as already noted.
- Channelling within the fracture could possibly further reduce the F-factor, but not necessarily, see /Rasmuson and Neretnieks 1986/. If the transmissivity data already reflect the channels rather than averages of fracture planes further reduction due to channelling is not needed and if channels are approaching circular holes radial diffusion will partly compensate for the decrease in surface area in the hole. Consideration of channelling within fractures will be made in SR-Can.
- The ranges of porosity and formation factors for the major rock types in the Laxemar surbarea are within the ranges considered in SR-97. Also the estimated sorption properties are essentially within the range of the values considered for SR 97, apart for Ra(II), under saline conditions, and for Am(III), where lower values are found. These differences, however, do not depend on site specific differences compared with

the SR-97 sites, and the implied reduction of the retention of these nuclides is small. Nevertheless, the uncertainty in the sorption properties and its impact on radionuclide transport need careful assessment in SR-Can. Furthermore, the available data are currently insufficient for establishing quantitative relations between transport parameters and other properties such as lengths, orientations and hydraulic properties of fractures and deformation zones.

Despite the stated limitations and uncertainties, there is no reason, from a safety point of view, not to continue the Site Investigations at the Laxemar subarea. There are still various matters to resolve and the safety would eventually need to be verified through a proper safety assessment based on a more complete data set.

## 4.2 Feedback to the continued site characterisation

The Site Descriptive Model, i.e. SDM L1.2, is based on the Initial Site Investigation of the Laxemar subarea, and the model report /SKB 2006a/ concludes that important steps in the modelling have been taken and more of the uncertainties are now quantified, or explored as alternatives. Notwithstanding, several hypotheses remain to be tested and some uncertainties remain to be quantified. Notably, there are questions about the representativity of the rock mechanics, thermal, hydrogeological and hydrogeochemical samples. There are generally few data at depth from the rock domains where the potential repository might be located.

This Preliminary Safety Evaluation shows that only some uncertainties have safety implications and would need further resolution. The following feedback is provided to the site investigations and the associated site modelling.

- Reducing the uncertainty on the deformation zone geometry and character within the subarea will be needed to firmly ensure the suitable deposition volumes. The current uncertainty in the character and geometry of the deformation zones in the area means that the layout of step D1 would likely need to be substantially altered when a less uncertain description is available. The additional data as suggested in SDM L1.2 and subsequent evaluation appear appropriate for this purpose.
- There is substantial, and as yet, not quantified, uncertainty in the DFN-model. More data are needed from the potential repository volume, as further discussed in Chapters 12 and 13 of SDM L1.2, but there is a limit on the degree to which these uncertainties can be reduced using only information from surface-based investigations. Further reduction of the uncertainties, if needed, would probably only be possible from the underground, detailed investigation phase. Presently, the overall strategies for detailed investigations during the construction phase are under development within SKB. Whatever strategies are expressed now, these have to be adapted to the insights gained during tunnel excavation, regarding both the identification of any site-specific signature of long fractures/small deformation zones and the implications of identification of such signatures for the training of geologists for the required field work and detailed modelling.
- Efforts need also be spent on improving the DFN-modelling. There are assumptions made in current models that could be challenged and there seems to be room for making better use of the borehole information. It is especially important to provide robust estimates of the intensity of large fractures and features, e.g. $P_{32}$ and the $k_r$ parameter in the power-law distribution, and further efforts should be spent on providing good support for the possible range of these parameters. In contrast, details of the orientation distribution of fractures are of much less importance.

- Considering the uncertain and relatively high stress levels in Stress Domain I, in combination with the comparatively low Uniaxial Compressive Strength of the intact rock, further reductions in the uncertainties in stress and rock mechanics properties are needed. There is a need to obtain representative data from all important rock types in the potential repository volume. The additional data suggested in Chapter 13 of SDM L1.2 are considered appropriate to fill these needs. Also, the issue of spalling due to the thermal load will require additional analyses, as already envisaged for SR-Can. This may also lead to additional data demands.
- Even if the thermal requirements and preferences are met, further reduction of uncertainties in the spatial variability and scaling of thermal conductivity would allow for a more efficient design. In order to justify a significant reduction of the canister separation distance making the layout more efficient, more representative data from the rock types in the repository volume are needed. The planned data and modelling envisaged in Chapter 12 and 13 in SDM L1.2 appears justified and would most likely allow for a sufficiently well defined layout after the site investigation phase. In addition, a more detailed adaptation of the layout to the local thermal properties could possibly be made during the detailed investigation phase.
- Given the uncertainties in the hydraulic data and in the DFN model, the hydraulic DFN analysis should be seen as indicative. There is a high variability of transmissivity within boreholes and the significance of the currently assumed depth dependence could be questioned. There is also high variability in transmissivity between boreholes, and the relatively few boreholes imply uncertainty when extrapolating the statistics of a single borehole to larger area, i.e. the significance in attributing different hydraulic properties to different rock domains is not fully established. The importance of anisotropy may also have been underestimated in opting for a simplified hydraulic DFN model with the same transmissivity relationships for all fracture sets. More data from the rock mass of the potential repository volume are needed before it is meaningful to more elaborately try to bound the uncertainties and spatial variability of the rock mass hydraulic properties of the Laxemar subarea. More detailed suggestions for how to reduce the uncertainties are given in the SDM L1.2, but also additional efforts may be needed.
- Comparing the hydrogeochemical and hydrogeological descriptions suggest agreement in the conceptual understanding, but there are still several quantitative uncertainties in both descriptions. Representative data from repository depth at the Laxemar subarea are needed. There is also a lack of data on water composition in the low conductive fractures and in the matrix. This means that even if the hydrogeochemical requirements and preferences are met, further reduction of uncertainties in the spatial distribution at depth is desirable to further improve the understanding of the hydrogeochemistry and would thus enhance the safety case. The additional data and evaluations suggested for this in SDM L1.2 seem appropriate.
- In order to have a full evaluation of the redox buffering capacity of the geosphere, more mineralogical data determinations of, Fe(II) and sulphide content of the rock and evaluations of the amount of fracture minerals in contact with the flowing water would be needed.
- The estimates of the transport resistance entail many uncertainties, and this will call for a careful analysis within SR-Can and in the following phases of the Site Investigations. More boreholes and subsequent assessment of the data will be needed to determine better bounds of the transport resistance. It needs to be remembered that the analysis in SDM L1.2 is based on data that do not fully represent the potential repository volume of the Laxemar subarea, as already noted above. There is a need to reduce this uncertainty in the site description. Also reducing the other uncertainties in the hydrogeological DFN-model is needed in order to narrow the bounds given by the first-order evaluation provided in SDM L1.2.

- Existing data on the migration properties of the rock do not suggest any strong spatial variation or strong correlation between rock type and migration properties. The uncertainties are more of a conceptual nature, as will be further assessed within SR-Can. Nevertheless, more in situ data on the migration properties of the rock would enhance the safety case. Better feedback on this issue will be available in relation to the full migration analysis made within SR-Can.

## 4.3 Implications for design

The assessments made for the PSE also suggest some implications for design, some of which are of a generic character to be considered also for other sites. The most important such feedback is given below.

Compared with the safety requirement, see Section 3.2.1, the design rules for discarding canister positions due to potential intersections with discriminating fractures or deformation zones seem to be too restrictive. For this reason SKB has now started a project aiming at estimating the probability of finding deposition holes intersected by discriminating fractures or deformation zones. This assessment should also produce more realistic estimates of the degree-of-utilisation.

Considering the recently relaxed thermal requirement, the current canister separation distance implies a considerable margin to the 100°C criterion for the peak buffer temperature. In fact, even a canister spacing of 6 m would possibly be sufficient for satisfying the thermal requirement on the buffer. However, in order to justify reducing the canister separation distance, making the layout more efficient, further reduction of uncertainties in the spatial variability and scaling of thermal conductivity would be necessary, as stated above. Furthermore, the thermo-mechanical consequences of a smaller canister separation distance may also need attention.

The relatively high and spatially varying hydraulic conductivity require special attention to implications of high inflow rates and their impact on loss of deposition holes and special grouting needs.

## 4.4 Implications for later safety assessments

Table 3-1 lists planned site-specific analyses in coming safety assessments. This PSE highlights some issues that will need special or additional attention in any full long-term safety assessment of a final repository for spent nuclear fuel at the Laxemar subarea. Most of the issues are rather generic in nature and thus warrant consideration in future safety assessments of other sites.

The percentage of deposition holes intersected by fractures with radii larger than 75 m given in this report does not consider the probability of identifying such large fractures and thus avoiding disposing waste in inappropriate deposition holes. For the Safety Assessment, there is also a need to consider this probability. Preliminary assessments, focusing on finding how precise such practical identification would need to be in order to make the impact of post-glacial faults negligible, will be made in SR-Can.

Despite the relatively low intact rock strength in relation to the rock stresses, spalling during construction and operation appears to be a minor problem and with no implications on long term safety. However, there needs to be attention to the likelihood and consequences of spalling, due to the thermal load, in deposition holes. Such spalling may not imply a major problem, since it will not progress very deep in the deposition hole wall. Still, both the likelihood and the consequences of thermal spalling of deposition holes will need to be assessed in SR-Can.

The relatively high and spatially varying hydraulic conductivity in the repository volume require special attention. Potentially high inflow rates to deposition holes raise concerns about piping/erosion of the buffer during resaturation. High local conductivity may also enhance radionuclide releases in case the canister is breached.

Upscaling using various assumptions in the DFN-model is needed to provide more quantified uncertainty ranges of the transport resistance for application within Safety Assessment. Furthermore, channelling within the fracture may also affect the F-factor. Such upscaling and consideration of channelling within fractures will be performed as part of SR-Can.

The uncertainty in the sorption properties and its impact of radionuclide transport need careful assessment in SR-Can. The site-specific information on the migration properties of the rock needs also to be complemented by more generic data and by consideration of how they are affected by the conceptual uncertainties in the migration processes. Combining site-specific and generic data in the context of conceptual uncertainty is an important part of a safety assessment and will be done in SR-Can, but lies outside the scope of this PSE.

It seems that the future evolution of the hydrogeochemistry could be sufficiently well bounded by the ranges of the properties within and between the four water types identified in the Laxemar subarea. In the safety assessment, it should be assessed whether there could be any process or condition that would invalidate such an assumption.

Finally, there are other site specific issues, not related to the rock properties, that need to be considered in a full safety assessment of the Laxemar subarea. An example of such an issue is the potential impact of the Äspö HRL.

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