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Preliminary safety evaluation for the Forsmark area

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

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Preface

This report presents the preliminary safety evaluation (PSE) of the Forsmark area, based on data from SKB's Initial Site Investigation stage. The report contains many references to specific sections of the Forsmark Site Descriptive Model report /SKB, 2005a/. In order to enhance the reading of this PSE, it is preferable that the reader has access to this report to provide extended background and context.

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Comments have been provided by Jan-Olof Selroos, Ignasi Puigdomenech and Raymond Munier of SKB's safety assessment team on issues regarding hydrology/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, Kristina Skagius Kemakta Konsult AB 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, Gunnar Gustafsson, Jordi Bruno and John A Hudson.

Stockholm, August 2005

Allan Hedin
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Summary

The main objectives of this Preliminary Safety Evaluation (PSE) of the Forsmark area 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 evaluation shows that, even considering remaining uncertainties, the Forsmark area *meets all stated safety requirements* and *preferences*. Consequently, from a safety point of view, there is no reason not to continue the Site Investigations of the Forsmark area. There are still uncertainties to resolve and the safety would eventually need to be verified through a full safety assessment. Nevertheless, this Preliminary Safety Evaluation demonstrates that it is likely that a safe repository for spent nuclear fuel of the KBS-3 type could be constructed at the site.

Only some of the uncertainties noted in the Site Descriptive Model have safety implications and 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 inside the target area would be needed to more firmly define locations of the suitable deposition volumes.
- There is substantial uncertainty in the Discrete Fracture Network model. Efforts need to be spent on reducing these uncertainties. During the Site Investigation Phase this can partly be achieved with more data, but there is a limit on the extent to which these uncertainties can be reduced using only surface-based information. Further reduction of the uncertainties, if needed, would probably only be possible from the underground, detailed investigation phase.
- 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 better use of the borehole information. It is particularly important to provide robust estimates of the intensity of large fractures and features, e.g. as characterised by the k parameter in the power-law distribution and further efforts should be spent on providing good support for the possible range of this parameter. In contrast, details of the orientation distribution of fractures are of much less importance.
- Considering the high and uncertain stress levels that have been observed, further reduction of the uncertainties in stress and rock mechanics properties is needed. Also, the issue of spalling due to the thermal load originating from the waste may require additional analyses and lead to additional data demands.

- Even though 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 (compact) design. Issues worth considering include assessing the potential anisotropy of the thermal data and the size distribution of the subordinate rock types within RFM029.
- The current model indicates very low hydraulic conductivities at potential repository depth, but additional site data are needed in order to confirm the extent of the low permeability volumes. The uncertainties in the spatial variation and upscaling of the hydraulic properties warrant further studies. Furthermore, reducing the uncertainty in hydraulics of the fracture network would allow for much less pessimistic handling of the transport resistance in the rock mass.
- The groundwater composition meets all requirements and preferences, but further reduction of uncertainties would improve the basis for assessing the future evolution of the groundwater composition. For example, a more definite explanation of the high uranium content found at depth is needed.
- In order to have a full evaluation of the redox buffering capacity of the geosphere, more mineralogical data, Fe(II) and sulphide content of the rock and amount of fracture minerals in contact with the flowing water would be needed.
- There is a need, if possible, to reduce the uncertainty in characterising the effects of channelling on radionuclide migration. However, this can only partly be achieved by new measurement approaches. Further attention to modelling, with different alternatives and careful scrutiny of assumptions, appears to be the way forward.
- The assessed migration properties of the rock matrix (porosity and formation factor) comply with the preferred values. However, the values are based on few samples only and evaluation of more samples would thus further substantiate this conclusion. Better feedback on this issue will be available in relation to the full migration analysis made within the on-going full safety assessment SR-Can.

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 the other sites. The most important such feedbacks are:

- 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 actually finding the deposition holes intersected by large fractures. This assessment will also produce more realistic estimates of the degree-of-utilisation.
- The 6 m spacing of canister deposition holes, suggested in the repository design, appears sufficient. At least locally, it may be possible to use even shorter canister spacing, or to reduce the spacing between the deposition tunnels, but this would require a more detailed understanding of the spatial variability of the thermal properties.

Finally, this PSE also highlights issues that would have to be considered if the Forsmark area 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 likelihood and the consequences of thermal spalling of deposition holes, and assessing the consequences of the very low permeability of the rock mass.

Utökad sammanfattning

Målen för denna preliminära säkerhetsbedömning av Forsmarks kandidatområde 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.

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 sker 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, trots kvarvarande osäkerheter, att Forsmarks kandidatområde *uppfyller alla ställda krav och önskemål*. Beträffande *ställda krav* kan följande slutsatser dras:

- Noggranna undersökningar visar att Forsmarks kandidatområde inte har malmpotential. Bergartsfördelningen är typisk för granitisk berggrund och kvarvarande osäkerheter i bergartsfördelning har liten betydelse ur säkerhetssynpunkt.
- En modell över bergets deformationszoner har tagits fram, även om osäkerheter kvarstår i modellen. Det är klart möjligt att placera ett tillräckligt stort förvar med tillräckliga respektavstånd till deformationszoner inom det fokuserade området för fortsatta platsundersökningar, dvs. en del av kandidatområdet, även om en låg nyttjandegrad antas.
- Endast några få procent av alla tänkbara deponeringshål korsas av så stora sprickor eller zoner, dvs. sådana med en radie större än 50 m, att de inte kan användas för deponering. Den exakta andelen är dock osäker på grund av osäkerheter i modellen av bergets sprickor.
- Bergspänningarna är höga på större djup. Ett förvar kan dock konstrueras, åtminstone ned till 500 m nivån, utan att det blir omfattande problem med smällberg eller annat bergutfall. Om deponeringstunnlarna orienteras vinkelrätt mot högsta horisontella huvudspänningen ökar risken för smällberg markant under nivån 450 m. Risken elimineras för alla förvarsdjup om tunnlarna orienteras parallellt med högsta huvudspänningsriktningen. Det är inte heller troligt att det uppstår smällberg i de vertikala deponeringshålen. Över 400 m nivån är det mycket låg sannolikhet och även nere vid 650 m nivån är sannolikheten mindre än 1 procent. Det finns dock osäkerheter i analyserna och prognosen över bergspänningarna har lägre tilltro under nivån 500 m.
- Bergmassan har god värmeledningsförmåga. Det är oproblematiskt att ta fram en förvarslayout som tillgodoser ställda temperaturkrav på kapselytor och buffert.

- 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. Även referensvattnen uppfyller de hydrogeokemiska kriterierna, vilket betyder att det är troligt att grundvattnets sammansättning kommer att förbli inom önskade gränser även i framtiden.

Utvärderingen visar också att Forsmarks kandidatområde uppfyller alla, ur säkerhets-synpunkt, ställda önskemål. I vissa fall skulle dock ytterligare reducering av osäkerheterna i platsbeskrivningen kunna ge mer robusta säkerhetsargument, men all sådan reducering behöver inte nödvändigtvis göras under platsundersökningsskedet. Följande, mer detaljerade, slutsatser kan göras beträffande *ställda önskemål*:

- Bergspänningsnivåerna är relativt höga. På 500 m djup är högsta horisontella spänningen i medel omkring 45 MPa och uppskattningen är dessutom osäker. Det innebär att det måste fästas speciell uppmärksamhet vid konstruktions- och stabilitetsfrågor, särskilt om förvaret placeras djupare än 500 m.
- Beskrivningen av bergmassans vattengenomsläpplighet är osäker, speciellt beträffande den rumsliga fördelningen av bergets hydrauliska egenskaper. Modellresultat visar dock att ställda önskemål uppfylls väl. Inom de tilltänkta förvarsvolymerna finns det enligt modellen bara mycket få block med en vattengenomsläpplighet större än 10^{-8} m/s. Osäkerheterna behöver dock reduceras innan mer säkra prognoser kan göras.
- Modellresultat visar även att bergets flödesberoende transportegenskaper, darcyflöde och transportmotstånd, uppfyller ställda önskemål, men analyserna är osäkra. Resultaten bygger dels på en grundvattenflödesmodell uppställd i regionalskala, dels på mer enkla överslagsberäkningar. Den regionala grundvattenmodellen har inte tillräcklig upplösning och det finns dessutom stora osäkerheter om flödesfördelningen och om det förekommer s.k. kanalbildning genom berget. Överslagsberäkningen ger dock tämligen robusta lägsta gränser för bergets transportmotstånd, även med hänsyn till kanalbildning, men osäkerheterna är ända relativt stora. Olika antaganden om kanalbildning har stor inverkan på resultaten.
- Bergmatrisens transportegenskaper (porositet och formationsfaktor) uppfyller ställda önskemål, men resultaten bygger bara på ett fåtal provtagningar.

Sammanfattningsvis gäller att det från säkerhetssynpunkt inte finns någon anledning att inte fortsätta platsundersökningarna i Forsmark. Det finns dock kvarvarande osäkerheter och om ett förvar skulle lokaliseras till området behöver säkerheten verifieras i en fullständig säkerhetsanalys. Den preliminära säkerhetsvärderingen visar dock att det är troligt att ett säkert KBS-3-förvar för använt kärnbränsle kan förläggas till området.

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. Följande återkoppling görs till platsundersökning och tillhörande platsmodellering.

Genom att minska osäkerheterna i geometrin for deformationszonerna inom det prioriterade området skulle en mer precis förvarslayout kunna tas fram, även om gjorda känslighetsstudier visar att den nödvändiga förvarsvolymen inte påverkas så mycket av osäkerheter i denna geometri. De kompletterande undersökningar som för detta syfte föreslås i platsmodellrapporten verkar 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 i den fördelningsfunktion som används in 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 kompletterande undersökningar som för detta syfte föreslås i platsmodellrapporten verkar lämpliga. Det finns dock, sannolikt, en gräns för hur mycket ytbaserade undersökningar kan reducera osäkerheterna. Om ytterligare osäkerhetsreduktion behövs kan detta troligen endast göras genom 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.

Med tanke på de höga och osäkra spänningsnivåerna behöver osäkerheterna i bergspänningar och bergets mekaniska egenskaper reduceras ytterligare. De kompletterande undersökningar som för detta syfte föreslås i platsmodellrapporten verkar lämpliga. Dessutom kan analysen av eventuella smällbergsfenomen i deponeringshåll 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 den termiska ledningsförmågan skulle dock tillåta en ännu mer effektiv layout. Speciellt uppmärksamhet bör därvid fästas vid den tänkbara anisotropin och storleksfördelningen hos sekundära bergarter, med avvikande ledningsförmåga, inom bergdomän RFM029. De kompletterande undersökningar och analyser som för detta syfte föreslås i platsmodellrapporten verkar lämpliga.

Den nuvarande modellen indikerar att vattengenomsläppligheten på förvarsnivå är mycket låg, men det behövs ytterligare data för att bekräfta utbredningen av dessa lågpermeabla volymer, liksom för att bättre beskriva den rumsliga fördelningen av de vattenförande områdena. Om osäkerheterna för spricknätverkets hydrauliska egenskaper skulle kunna minskas, skulle detta möjliggöra en mycket mindre pessimistisk uppskattning av bergets transportegenskaper. De kompletterande undersökningar och analyser som för dessa syften föreslås i platsmodellrapporten verkar lämpliga.

En reducering av osäkerheterna i den hydrogeokemiska modellen skulle öka förståelsen och därmed ge ytterligare säkerhetsargument. Det krävs till exempel en mer slutgiltig förklaring till de höga uranhalter som har hittats även på större djup. För att tillåta en mer fullständig analys av geosfärens redoxbuffringsförmåga behövs mer mineralogiska data, Fe(II) och sulfidinnehåll i bergmatrisen och mängden sprickmineral i kontakt med det flödande vattnet. De kompletterande undersökningar och analyser som för dessa syften föreslås i platsmodellrapporten verkar lämpliga.

Osäkerheterna om eventuellt kanalbildning behöver, om möjligt, reduceras. Det är bland annat tänkbart att data från borrhåls-TV kan användas för att uppskatta kanalernas vidd, men mätningar kan bara delvis minska osäkerheterna. Ytterligare fokusering på modellering, med olika alternativ och noggrann analys av gjorda antaganden behövs.

Bedömningen av bergmatrisens transportegenskaper (porositet, formationsfaktor och K_d) bygger bara på ett fåtal prov. Analys av fler prov skulle öka förståelsen.

Inverkan på 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 för 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.

För att undvika smällbergsproblem är det väsentligt att deponeringstunnlarna orienteras parallellt med största horisontella huvudspänningsriktningen. Detta görs också i den föreslagna design D1.

Det föreslagna kapselavståndet om 6 m verkar tillräckligt. Med nuvarande beskrivning av värmeledningsförmågans rumsliga variation skulle väsentligen alla kapslar ha en maxtemperatur på kapselytan under 100°C. Lokalt skulle även kortare avstånd mellan kapslar, eller mellan deponeringstunnlar, vara möjligt men då behövs en mer detaljerad kunskap om de termiska egenskapernas rumsliga variation.

Inverkan på kommande säkerhetsanalyser

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

Bedömningen av andelen kapslar som korsas av sprickor eller deformationszoner med radie över 50 m, som redovisas i denna rapport, tar inte hänsyn till möjligheten att hitta sådana deponeringshål och därmed undvika att deponera kapslar i dessa. 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 de höga bergspänningarna, verkar smällbergsfenomen under bygge och drift vara hanterbara problem och med liten inverkan på den långsiktiga säkerheten. Möjligheterna till och konsekvenserna av smällbergsfenomen i deponeringshål på grund av termolasten efter deponering behöver dock beaktas. Sådan uppsprickning behöver inte utgöra något allvarligt problem för den långsiktiga säkerheten eftersom uppsprickningen blir mycket lokal och sedan stabiliseras. Fenomenet och dess konsekvenser kommer dock att studeras inom SR-Can.

Det mesta av bergmassan på tänkbart förvarsdjup verkar ha mycket låg vattengenomsläpplighet. Detta är generellt en fördel vid fördröjningen (retentionen) av de radionuklider som skulle kunna komma ut om isoleringen bryts, men det innebär också att det kan ta mycket lång tid för bufferten att mättas och nå sitt svälltryck. Detta behöver inte utgöra något problem, men frågan behöver ändå studeras inom SR-Can.

De relativt enkla överslagsberäkningarna av bergets transportmotstånd demonstrerar betydelsen av eventuell kanalbildning, men analysen visar också att det går att sätta en undre gräns för transportmotståndet. SR-Can kommer att behöva studera dessa osäkerheter mer ingående liksom möjligheten till att gränssätta transportmotståndet.

Fördröjningen för en radionuklid är ämnesspecifik och betydelsen of 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. En sådan analys 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 volymen. I säkerhetsanalysen behövs dock en värdering om det finns någon process eller annan indikation som skulle kunna falsifiera 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. Exempel på sådana frågor är den tänkbara inverkan av de näraliggande kärnkraftverken, inverkan av kraftkabeln till Finland eller inverkan av ett djup gruvschakt placerat i närheten men utanför den tektoniska linsen.

Contents

1 Introduction 15
1.1 Purpose and objectives 15
1.2 Overview of methodology 16
1.3 Developments since the planning document and implications for the PSE 17
1.4 INSITE review of PSE planning document 17

2 Basis for the safety evaluation 19
2.1 Site descriptive model 19
2.1.1 Investigations and available data 20
2.1.2 The site descriptive model report 21
2.1.3 Main features of the Forsmark site 21
2.1.4 Overall confidence in the modelling 22
2.2 Preliminary layout 23
2.2.1 Methodology 24
2.2.2 Applying the methodology to the Forsmark area 25

3 Analyses and comparison to criteria 27
3.1 Overview and means of evaluation 27
3.1.1 Analyses considered in the PSE 27
3.1.2 Basis of comparison 29
3.2 Geological features of relevance to safety 29
3.2.1 Criteria and other safety considerations 29
3.2.2 Rock type distribution 31
3.2.3 Assessment of ore-potential 33
3.2.4 Deformation zones and fractures 34
3.2.5 Layout adaptation to deformation zones 40
3.2.6 Probability of deposition hole intersections with fractures and deformation zones 42
3.2.7 Safety implications 45
3.3 Rock mechanics 46
3.3.1 Criteria and other safety considerations 46
3.3.2 Stress and rock mechanics properties 47
3.3.3 Mechanical stability during construction and operation 50
3.3.4 Safety implications 51
3.4 Thermal analyses 52
3.4.1 Criteria and other safety considerations 52
3.4.2 Thermal properties and initial temperature 53
3.4.3 Thermal evolution of canister surface, buffer and near field rock for present climate conditions 54
3.4.4 Safety implications 58
3.5 Hydraulic analyses 59
3.5.1 Criteria and other safety considerations 59
3.5.2 Hydraulic properties and effective values of permeability 60
3.5.3 Groundwater flow calculations and particle discharge points 66
3.5.4 Safety implications 68

3.6 Hydrogeochemistry 69
3.6.1 Criteria and other safety considerations 69
3.6.2 Current groundwater composition 70
3.6.3 Safety implications 74
3.7 Radionuclide transport 75
3.7.1 Criteria and other safety considerations 75
3.7.2 Migration properties of the rock matrix 76
3.7.3 Flow-related migration parameters 77
3.7.4 Safety implications 82
3.8 Importance of analyses previously foreseen but now omitted from the PSE 83
3.8.1 Drawdown and upconing 83
3.8.2 Influence of grouting and construction materials 84
3.8.3 Transmission calculations and transport modelling 84
3.8.4 Near-surface hydrology 84

4 Conclusions and recommendations 85
4.1 Overall findings regarding long-term safety 85
4.2 Feedback to the continued site characterisation 86
4.3 Implications for design 88
4.4 Implications for later safety assessments 88

5 References 91

Appendix A A note on flow and transport in sparse networks – Implications for the Forsmark site 95

1 Introduction

This report is a Preliminary Safety Evaluation (PSE) of the Forsmark area being investigated by SKB. A similar evaluation has been conducted for the Simpevarp subarea /SKB, 2005e/, and a similar evaluation will be conducted for the Laxemar subarea.

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 storing 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 deep repository where the canisters will be deposited.

For this reason, SKB pursues site investigations for the deep 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. The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The candidate area is located along the shoreline of Öregrundsgrepen and it extends from the Forsmark nuclear power plant and access road to the SFR-facility in the northwest towards Kallrigafjärden in the southeast. The candidate area is approximately 6 km long and 2 km wide, 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 Forsmark and reported in the preliminary Site Descriptive Model version 1.2 of the Forsmark Site /SKB, 2005a/.

A PSE is made at the end of the initial stage, based on available field data and preliminary layouts for the deep repository. A similar evaluation has been conducted for the Simpevarp subarea /SKB, 2005e/, and a similar evaluation will be conducted for the Laxemar subarea.

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 at comparing 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.

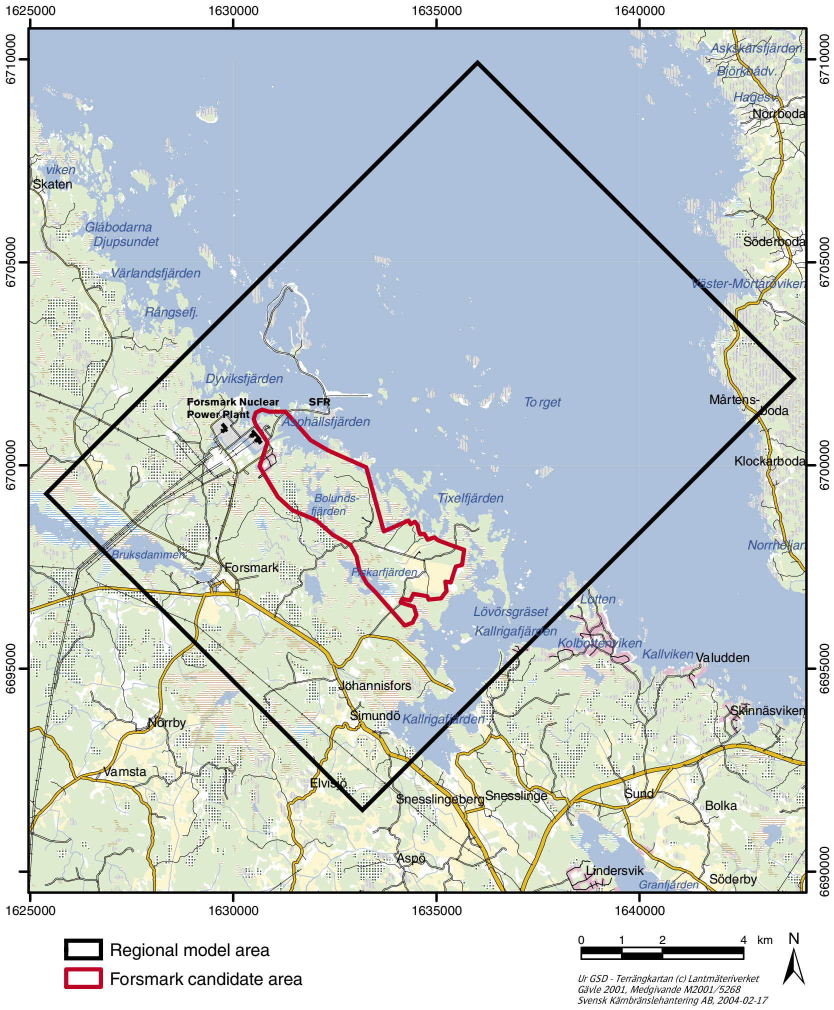

***Figure 1-1.** The Forsmark candidate area (red) and the regional model area (black) in the preliminary Site Descriptive Model. (Figure 1-2 of SDM F1.2) .*

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 different subject areas, i.e. 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, 2005a/ and the design work /SKB, 2005b/ 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 deep 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/ is already 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 deep repository is expected to be limited at the Simpevarp subarea in comparison with the two other candidate areas. A definite decision on what subarea to prioritize in Oskarshamn will be taken when a preliminary safety evaluation of the data from the Laxemar subarea has been made.

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 the further development. It is important already at the time of SR-Can to have established the likely viability of disposal at one or more 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 PSE planning document

The PSE planning document /SKB, 2002a/ has been reviewed by the SKI international review group INSITE /SKI, 2004/. The following main points were brought up in the review:

- The review states that "In general, the level of analysis planned for the PSE is what would be expected at this stage of a site investigation project, although there are some issues for discussion".

- The reviewers expressed concern that the result of the PSE would arrive too late to impact the Complete Site Investigation Phase.
- The respective roles of the PSE and the then envisaged limited safety assessment "SR-Met" were judged unclear by the reviewers.
- The reviewers considered there is also a need to assess the impact of thermal buoyancy effects, i.e. flow caused by the heat generation from the spent nuclear fuel, and to assess the potential development and significance of an Excavation Disturbed Zone (EDZ).

The reviewers also made various detailed comments and suggestions. Most of the suggested additions will be addressed in SR-Can (and the subsequent SR-Site) rather than in the PSE. Furthermore, there are several other issues, not brought up by the INSITE reviewers, which will be analysed in SR-Can.

In 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 are judged to be needed.

The SKB plans for Safety Assessments have evolved and the limited in scope "SR-Met" is now replaced by the full Safety Assessment SR-Can (see previous section).

Thermal buoyancy is not judged to be of significant importance to safety, see e.g. the SR 97 Process report /SKB, 1999/. Furthermore, the need to consider thermal buoyancy will be re-assessed in the SR-Can (and SR-Site) Process Reports. The development and properties of the EDZ will be addressed in SR-Can and updated in SR-Site.

2 Basis for the safety evaluation

This chapter provides reference to the Site Descriptive Model of the Forsmark area and to the engineering work that has been applied 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 Forsmark area version 1.2, /SKB, 2005a/ and denoted SDM F1.2 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, namely SDM F1.1 /SKB, 2004b/ and version 0 /SKB, 2002b/, are incorporated in model version 1.2. 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.

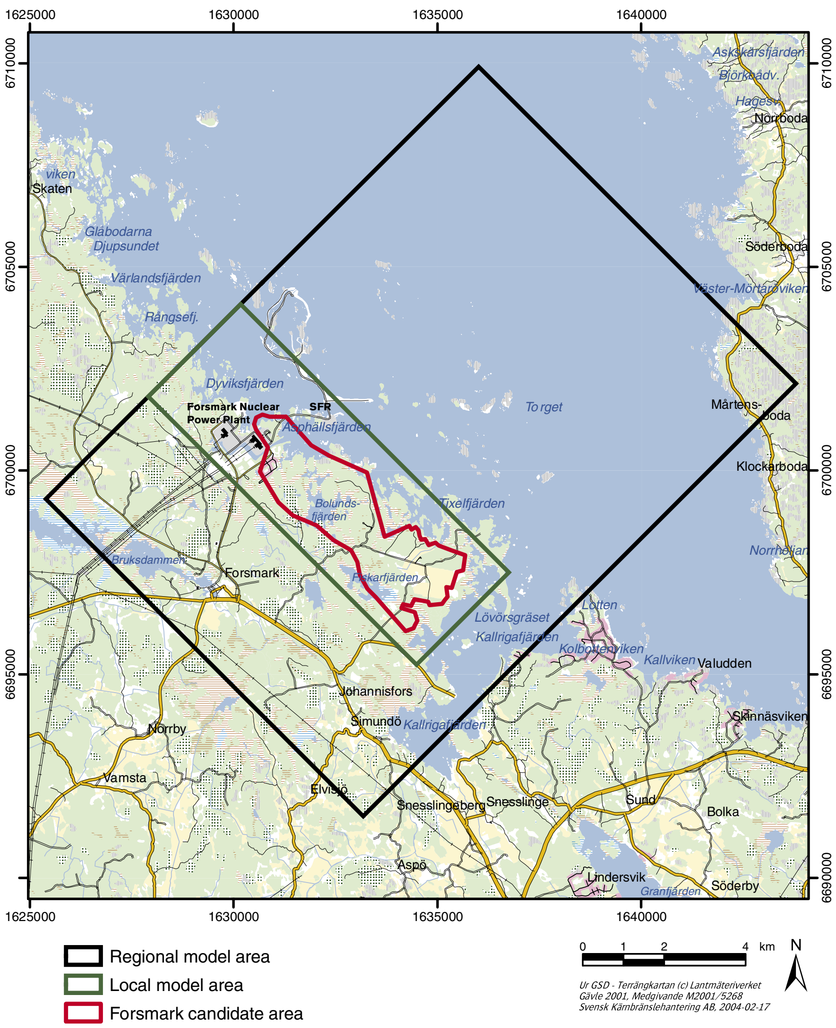

Figure 2-1. *Regional and local model areas, Figure 2-3 of SDM F1.2.*

2.1.1 Investigations and available data

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The candidate area is located along the shoreline of Öregrundsgrepen and it extends from the Forsmark nuclear power plant and access road to the SFR-facility in the northwest towards Kallrigafjärden in the southeast. The candidate area is approximately 6 km long and 2 km wide, see Figure 1-1.

Investigations have been in progress in the Forsmark area from about February 2002. The data freeze for the Forsmark 1.1 model version was set at April 31, 2003 and reported in the version F1.1 Site Descriptive Report /SKB, 2004b/. The data freeze for SMD F1.2 was set at July 31, 2004.

The surface investigations undertaken in the Forsmark area comprise airborne photography, airborne and surface geophysical investigations, lithological mapping of the rock surface, mapping of structural characteristics, investigations of Quaternary deposits including marine and lacustrine sediments in the Baltic and in lakes, meteorological and hydrological monitoring and measurements, hydrochemical sampling and analyses of precipitation, surface waters and shallow groundwater and various ecological inventory compilation and investigations.

The drilling activities up to the time of the last data freeze comprised:

- Five approximately 1,000 m long deep cored boreholes and two (one 500 m and one 100 m) cored boreholes in the immediate vicinity of two of the deep holes.
- Nineteen percussion-drilled boreholes with lengths ranging up to 200 m and reaching vertical depths down to 200 m.
- About 65 soil/rock boreholes through Quaternary deposits.

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, susceptibility, mineralogy, geochemistry, diffusivity, sorption properties, rock strength and thermal properties, and groundwater sampling for the hydrogeochemical analyses.

In addition to the new data, the "old data" that were identified during the compilation of data for model version 0 have been evaluated and/or inserted in the SKB databases SICADA and GIS in time for data freeze 1.2. These data include information from the siting and construction of the three nuclear reactors (Forsmark 1–3), the feasibility study for an underground interim storage facility for spent fuel at Forsmark, and the pre-investigations and construction of the final repository for low and intermediate level reactor waste SFR. However, it should be noted that these data have not undergone the same quality assurance process as the ones collected in the present site investigations. In the hydrogeochemical evaluation, available data from SICADA of groundwater conditions at near-by locations, such as SFR, and at other Swedish sites were used as background information together with data from Finnish sites (e.g. /Pitkänen et al. 1999/).

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 F1.2.

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 F1.2, 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 F1.2 (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 Forsmark area in a condensed form. Chapter 12 assess overall consistency and confidence in the description. Chapter 13 provides the overall conclusions of the work.

2.1.3 Main features of the Forsmark site

This section outlines the main features of the Forsmark area as summarised in Chapter 13 of SDM F1.2. The text is provided for overview, and features of direct importance for the PSE are more thoroughly discussed in Chapter 3.

The topography is gently undulating and of quite moderate elevations. Unconsolidated Quaternary deposits cover c. 85 percent of the land area and these deposits were formed during or after the latest glaciation. The Quaternary deposits are rich in $CaCO_3$. This together with the recent emergence of the area from the Baltic Sea affects the chemistry of surface and shallow groundwaters giving rise to high pH and high alkalinity.

The bedrock within the candidate volume of the rock is situated within the north-western part of a major tectonic lens that trends NW-SE along the coastal area of Uppland. The candidate volume is dominated by one lithological domain. The dominant rock type in this domain is a medium-grained metagranite (84 percent of the domain volume). Subordinate rock types are fine- to medium-grained metagranodiorite or metatonalite, amphibolite, pegmatitic granite or pegmatite and fine- to medium-grained granite.

Three major sets of deformation zones have been recognised with high confidence of existence in the Forsmark area: vertical and steeply, SW-dipping zones with WNW-NW strike, vertical and steeply-dipping, brittle deformation zones with NE strike and gently SE- and S-dipping brittle deformation zones. These gently dipping zones seem to play an important role in determining the properties of the Forsmark site.

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.

Thermal conductivity varies in space at various scales. Much of the rock has a rather high mean thermal conductivity, but there are minor parts with lower mean values. There are also some indications of anisotropy in thermal conductivity in lineated/foliated parts of the rock.

The rock mechanics properties show high strength and high stiffness. The rock stresses at Forsmark are relatively high compared with typical central Scandinavian sites.

The rock mass between the deformation zones in the candidate volume appears to be of very low permeability beneath the gently dipping deformation zone ZFMNE00A2 at depths below about the –360 m level. However, since there are few boreholes, the exact division into volumes of different hydraulic properties remains to be defined. In contrast, the upper part of the rock mass is rather permeable. Also, the transmissivity of deformation zones seems to vary with depth and dip, with higher transmissivity in the gently dipping zones than in the steeply dipping zones at comparable depths. However, down to c. 60 m depth, the zones are hydraulically very heterogeneous with transmissivities that vary over three orders of magnitude, thereby potentially evening out hydraulic gradients at depth.

Four main groundwater types are present at the Forsmark site: recent to young meteoric waters, old brackish water of marine origin with a Littorina Sea and glacial signature, older meteoric saline groundwater with a small glacial component, and a higher salinity type characterised by a more pronounced glacial signature. Modelling results indicate that re-equilibration reaction processes have been important for the establishment of the present groundwater composition, following the intrusion of Littorina Sea water into the rock. Most lines of evidence suggest that the microbiologically mediated sulphur system is the main redox controller in the deepest and most saline groundwater.

There are site specific data on porosity of the rock matrix and on the formation factor. Furthermore, there are indications that the formation factor (and the porosity) are dependent on the rock stress, which means that field tests and laboratory results do not provide the same results.

2.1.4 Overall confidence in the modelling

The understanding of the Forsmark area is addressed and discussed in Chapter 12 of the SDM F1.2 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 tentative conclusions as to the general understanding of the Forsmark area.

As discussed in Chapter 12 of SDM F1.2, 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. Such data have been scrutinised to determine that they are fit-for-purpose and then been either accepted for use or rejected. In addition, inaccuracies and biases are understood and accounted for in the subsequent modelling. Inaccuracies and biases in the field data are, with some exceptions, judged to be a minor source of uncertainty in the resulting model description.

Important modelling steps have been taken and more of the uncertainties are now quantified or explored as alternatives. However, several hypotheses remain to be tested and some uncertainties remain un-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. Important parameters and data where uncertainties could have direct implications for safety assessment (e.g. PSE) or repository engineering are:

- The occurrence, continuity, dip and thickness of deformation zones and the heterogeneity of their transmissivity, mainly in the target area.
- The size, intensity and transmissivity of fractures in the rock mass between deformation zones, mainly in the target area, including spatial variability and giving consideration to the possibility of dividing the rock mass into volumes with different hydraulic properties.
- The spatial and depth distribution of stress magnitudes and rock mechanics properties, mainly in the target area.
- Spatial variability in rock transport properties and correlations with flow paths.

The uncertainties for these parameters and data and their relevance for this PSE are further discussed in Chapter 3.

As demonstrated in section 12.4 of SDM F1.2, there are many important interactions between the different disciplines and many of these have been considered in the development of version 1.2 of the site descriptive model. It is obvious that geology provides an important input to many of the other disciplines by defining the geometrical framework and geological properties of rock domains, deformation zones and rock mass fracturing. However, to assure consistency in the site model there is also feedback from other disciplines to geology that should be utilised to improve confidence in the geological model. This feedback has to some extent been used in developing model version 1.2, but there are possibilities for further improvements in this area. An example of an important feedback during the development of model version 1.2 is the hydraulic confirmation that gently dipping deformation zones are major features for groundwater flow. Other important interactions concern the interplay between hydrogeology and hydrogeochemistry.

In general, the Forsmark 1.2 site descriptive model is in agreement with the current understanding of the past evolution as described in Chapter 3 of SDM F1.2. As the investigations proceed, the findings from the site continue to improve our understanding of past conditions, as exemplified in section 12.5 of SDM F1.2. The previously existing understanding of the site has been largely confirmed by the outcome of the version 1.2 modelling and no major surprises have occurred.

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 to:

- Present a facility description for the chosen site with a proposed layout for the deep 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 deep 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 deep repository facility to the point that it is possible to plan for the construction phase. Show and explain what technical solutions do not need to be engineered in detail in this phase.

Ultimately, the design work should lead to a layout D2, to be used in the application for the Deep 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 is applied to each site. The design methodology aims at addressing several design tasks. Each task addresses 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 deep 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 temperature on the canister surface?
- 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 size, excessive water inflow and instability? How is the loss affected by different criteria for rejection?
- C5. At what depth or over what depth range may it be suitable to build the deep 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 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 Forsmark area

A type D1 design, reported in /SKB, 2005b/ has been developed focusing on the "target area" of the Forsmark candidate area, see Figure 2-2. The selection of the target area is made and justified in the Forsmark Site Investigation Programme for further investigations of geosphere and biosphere /SKB, 2005d/.

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 –400 m and –500 m levels – the former is the reference option, as explained in /SKB, 2005b/. 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.

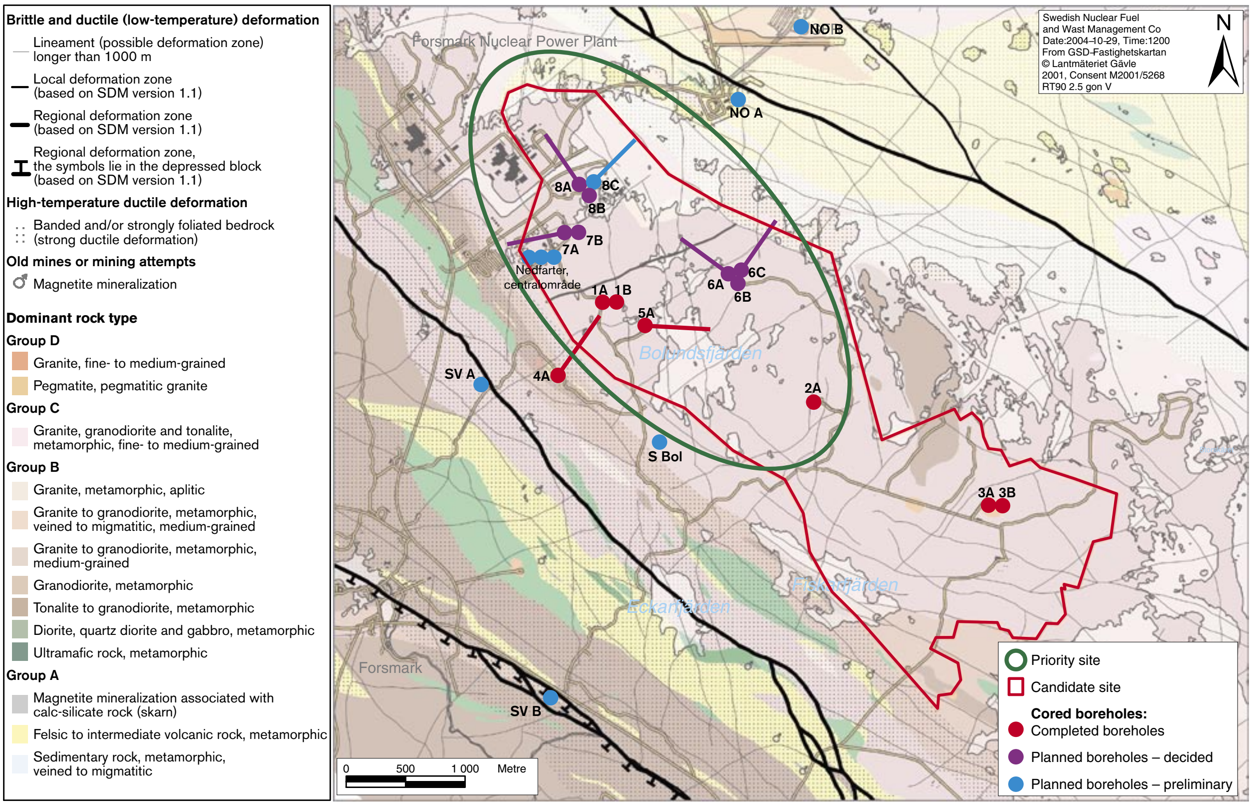

Figure 2-2. *The D1 design work for Forsmark has focused on the "target area" indicated in green (from /SKB, 2005d/, Figure 5: R-05-14).*

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, 2005a/ and the subsequent Rock Engineering exercise /SKB, 2005b/. 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 in the finings of the PSE:s 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 meetings 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 superregional, 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	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 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, ridge push etc.	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 etc.	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	SA
Colloid-facilitated transport	No	SA	SA
Biosphere analyses			
Near- surface hydrology			
– for present conditions	SDM	SDM	SDM
– for future climate conditions	No	SA	SA
Biosphere model for radionuclide transport			
– for present conditions	No	SA	SA
– for future climate conditions	No	SA	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, 2005a/ and the design work /SKB, 2005b/ 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 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 is *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 deep repository. It is also required that deposition tunnels and holes may not pass through or be located near regional and local major brittle deformation zones and that 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.

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 deep 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 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 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.

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

Table 3-2. Seismic influence distance, for earthquakes larger than M6, and Transition 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).	
	If > 100 m radius fractures avoided	If > 50 m radius fractures avoided	W/L Ratio 2%	W/L Ratio 1%
< 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. 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. The number of deposition holes with such intersections can be estimated from the discrete fracture network model as further discussed in section 3.2.6. It should also be noted that the number of deposition holes actually affected will, for several reasons, be much less than this number.

SKB currently explores practical means of how to identify 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, too 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. Additionally, only a few of the potentially problematic fractures will host slip exceeding the canister failure criterion. 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 the PSE.

3.2.2 Rock type distribution

According to SDM F1.2 the bedrock at the Forsmark site comprise Meta-igneous rocks with crystallisation ages in the time span pre-1,886 to 1,840 million years. In the model the lithology is represented by dividing the model volume into 35 rock domains, Figure 3-1. However, there are only few different rock domains inside the candidate volume.

The candidate volume at Forsmark is situated within a tectonic lens that extends along the Uppland coast from north-west of the nuclear power plant south-eastwards to Öregrund. The candidate volume is dominated by rock domain RFM029, Figure 3-1. Strongly deformed rocks, which are both foliated and lineated and which are, in part, also banded and inhomogeneous, comprise the rock domains along the south-western (e.g. RFM012, RFM018) and north-eastern (e.g. RFM021, RFM032) margins of the tectonic lens. Major folding and the development of less deformed rocks that are more lineated than foliated characterise the bedrock inside the lens. The tectonic lens developed when the rock units were situated at mid-crustal depths and were affected by penetrative but variable degrees of ductile deformation and metamorphism.

Quantitative estimates or qualitative assignment of the properties, including rock types and mineral composition, of all the thirty-five domains are listed in tabular format in Appendix 1 of SDM F1.2. Table 3-3 lists quantitative estimates of the proportions of different rock types in RFM029.

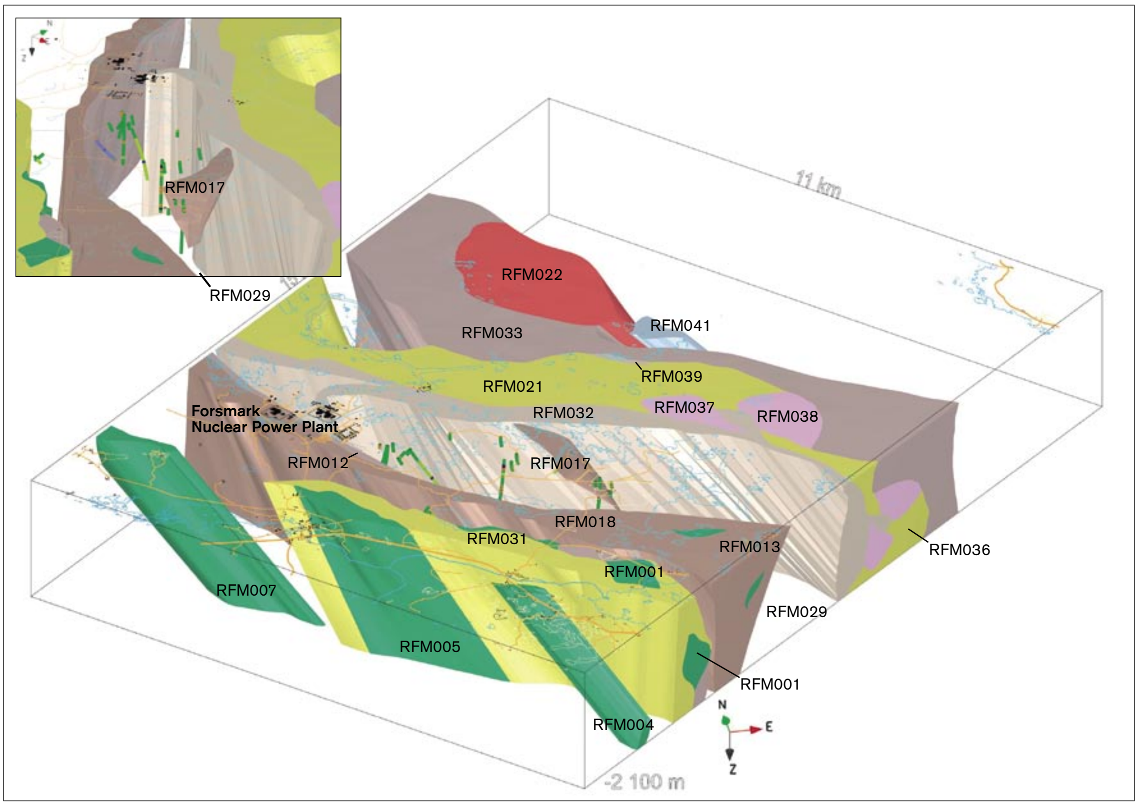

Figure 3-1. *Rock domain model, viewed to the north. Rock domain RFM029, as well as some other domains, are unshaded in order to show some of the major three-dimensional characteristics. The dominant rock type in each domain is illustrated with the help of different colours and boreholes are also shown. The figure also provides a detailed view of the tectonic lens and rock domain RFM029 within which most of the boreholes are situated. (Figure 5-55 of SDM F1.2).*

Table 3-3. Quantitative estimates of the proportions of different rock types in RFM029. Rock occurrences that are less than 1 m in borehole length have not been included in the calculations (from Table 5-23 in SDM F1.2).

Composition and grain size	RFM029
101057 Granite (to granodiorite), metamorphic, medium-grained	84%
101051 Granodiorite, tonalite and granite, metamorphic, fine- to medium-grained	10%
102017 Amphibolite	3%
101061 Pegmatitic granite, pegmatite	2%
111058 Granite, fine- to medium-grained	1%
103076 Felsic to intermediate volcanic rock, metamorphic	All occurrences < 1 m

According to SDM F1.2, the following more significant uncertainties remain after the development of the rock domain model, version 1.2:

- The composition, degree of homogeneity and degree of ductile deformation in the rock domains at the surface in the sea areas, especially at Öregrundsgrepen.
- The location of the boundaries between rock units in the north-western and south-easternmost parts of the candidate area, i.e. under Asphällsfjärden that lies between the nuclear power plant and Lake Bolundsfjärden, and around Storskäret.
- The extension at depth of all rock domains except RFM017, RFM029 and, to some extent, RFM007, RFM012, RFM018 and RFM023.
- The quantitative estimates of the proportions of different rock types in all rock domains, except for RFM012 and RFM029.

3.2.3 Assessment of ore-potential

An assessment of the potential of the Forsmark area for exploration and exploitation of metallic and industrial mineral deposits has been presented in /Lindroos et al. 2004/. A potential for iron oxide mineralisation and possibly base metals was recognised. A mineral resource map (Figure 3-2) shows how the areas that bear this potential are situated to the south-west of the candidate area, predominantly in the felsic to intermediate metavolcanic rocks. However, it is emphasised that the small iron mineralisations in this area have no current economic value and this judgement is also deemed to be valid in a long-term perspective /Lindroos et al. 2004/. Geochemical analyses of till at Forsmark provide support to this conclusion /Nilsson, 2003/.

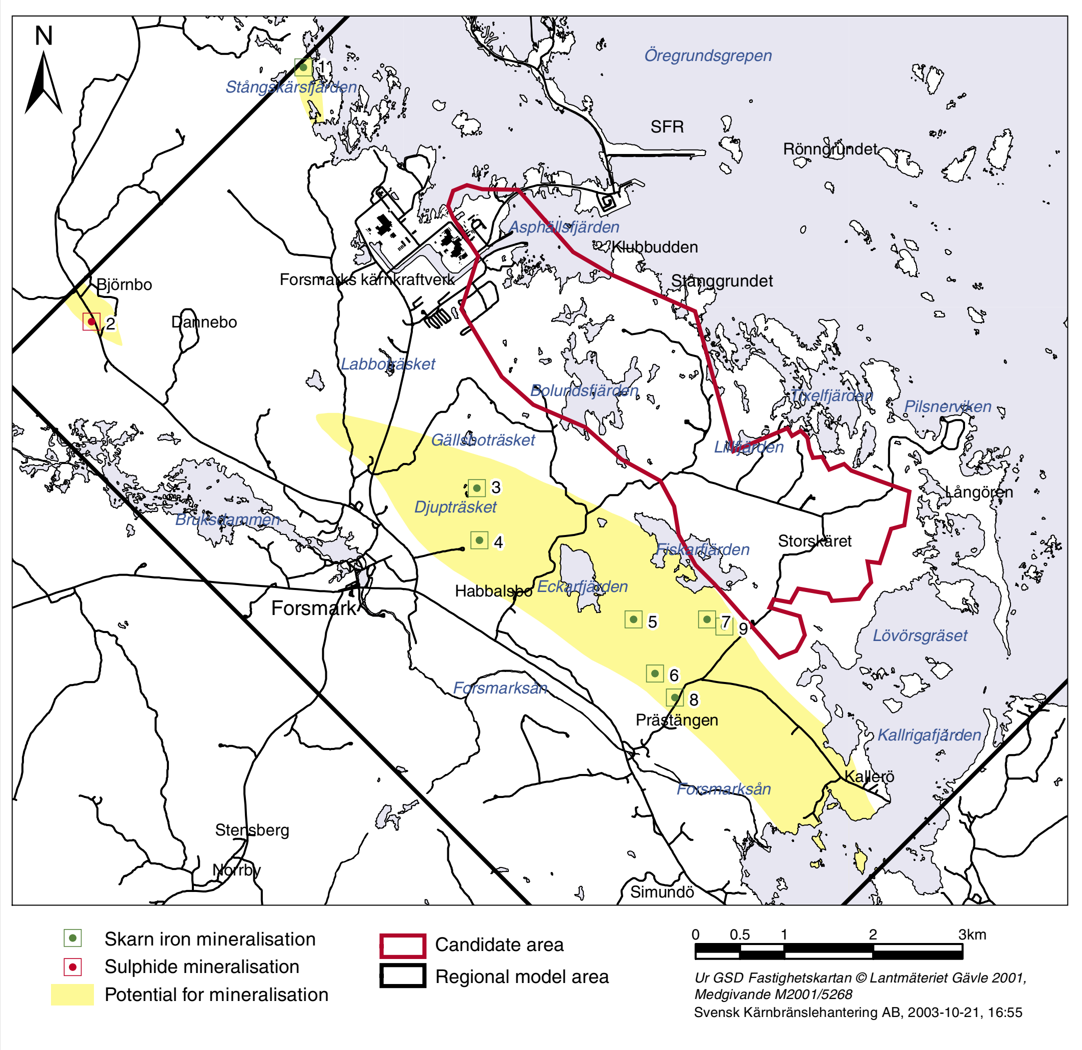

Figure 3-2. *Mineral resources map of the Forsmark area. The map shows the areas on the surface that are judged to have some exploration potential for mineral deposits (modified after /Lindroos et al. 2004/, Figure 5-14 of SDM F1.2).*

3.2.4 Deformation zones and fractures

Deterministic Deformation Zones

As further discussed in Chapter 5 of SDM F1.2 the amount of cored and percussion borehole data, in combination with a developed understanding of the geological significance of the seismic reflectors at the site, provided a sound foundation for the deterministic structural model of deformation zones. However, an alternative interpretation of lineaments within and immediately around the candidate area, by an independent working group /Korhonen et al. 2004/, has raised important questions concerning the recognition of lineaments, as well as the judgements made concerning especially their length and level of uncertainty. There also remains considerable uncertainty concerning both the along-strike and down-dip extensions of especially the gently-dipping, brittle deformation zones. For these reasons, three different deformation zone models have been generated in version 1.2 of the Site Descriptive Model. These are referred to as the *base model*, the *base model variant* and the *alternative model*.

In the base model (Figure 3-3a), vertical or steeply-dipping deformation zones that are generally longer than 1,000 m have been determined using an integration of fixed point intersections along boreholes and lineaments at the surface. The lineament information is supportive rather than deterministic in character. This approach is viable in two small volumes close to Lake Bolundsfjärden and the SFR repository. Outside these volumes, only vertical and steeply-dipping zones that are generally longer than 4,000 m are included in the base model. Gently-dipping zones in the base model have been recognised using an integration of fixed-point intersections in boreholes and seismic reflection data. This approach is only viable in the candidate area and its continuation towards the north-west. In the base model, several of these zones have been truncated along their strike against regional, vertical or steeply-dipping zones with WNW-NW strike. The base model variant (Figure 3-3b) only differs from the base model where it concerns against which WNW-NW zone the four gently-dipping zones (ZFMNE00A1, ZFMNE00A2, ZFMNE00C1, ZFMNE00C2) have been truncated. (Zones C1 and C2 are not visible in the figure). Thus, the difference between these two models only concerns the strike-length of these four zones. All deformation zones in the base model and its variant have been assigned high and medium levels of confidence of existence. Smaller zones and fractures, with a surface length expression of less than the cut-off values of 1 km and 4 km have not been included deterministically in the model, but are handled in a statistical way through discrete fracture network (DFN) models.

The alternative model (Figure 3-3c) follows more closely the procedures adopted in model version 1.1 for Forsmark. In this model, vertical and steeply-dipping zones that are generally longer than 1,000 m are described as deterministic features within the whole regional model volume. Outside the detailed Bolundsfjärden and SFR volumes, virtually all the vertical or steeply-dipping zones correspond solely to lineaments that are based on either magnetic or a combination of magnetic and other data. Most of the zones that have been recognised in this manner have been assigned a low level of confidence in existence. The gently-dipping zones in the alternative model have been determined in the same manner as in the base model. However, it should be noted that the alternative model essentially only differs from the Base Model outside the "target area".

Three major sets of deformation zones with distinctive orientations WNW-NW, NE and gently dipping have been recognised with high confidence at the Forsmark site. The bedrock in all sets is affected by oxidation with the development of a fine-grained hematite dissemination. Clay minerals are more prominent in the gently dipping set but are, nevertheless, present in some zones in the other sets. The general characteristics of the zones are given below:

- Vertical and steeply, SW-dipping zones with WNW-NW strike are regional and local major structures that show complex, ductile and brittle deformation. These zones define important marginal structures to the candidate area at the Forsmark site (see Figure 3-3).
- Vertical and steeply-dipping, brittle deformation zones with NE strike are local major (and local minor) in character. This set of zones is strongly dominated by sealed fractures and sealed fracture networks. They transect the candidate area at Forsmark and are prominent in the Bolundsfjärden area (see Figure 3-4).
- Gently SE- and S-dipping brittle deformation zones are local major in character and occur more frequently in the south-eastern part of the candidate area (Figure 3-4). Relative to the other three sets, there is an increased frequency of open fractures along the gently dipping set.

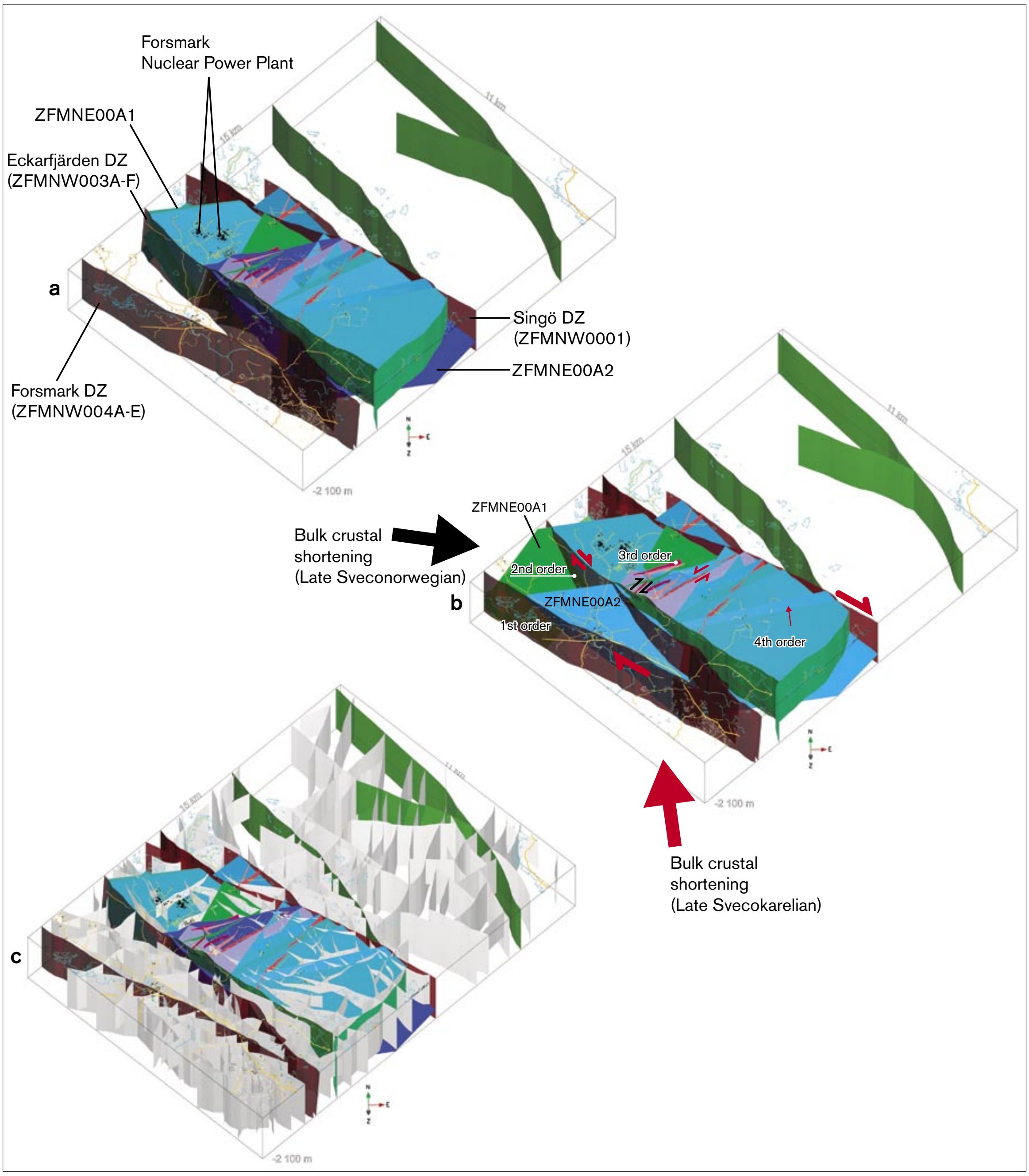

Figure 3-3. a) Base model for deterministic deformation zones, viewed to the north. The zones coloured in red-brown shades are vertical and steeply dipping zones with high confidence of existence, the zones coloured in blue shades are gently dipping zones with high confidence of existence, and the zones coloured in green shades are medium confidence zones irrespective of their dip. b) Base variant model. c) Alternative model, where the zones coloured in grey shades are vertical and steeply dipping zones with low confidence of existence. The inferred sense of displacement and orientation of the maximum principal stress direction, during both the formation and an important phase of reactivation of these structures, are shown in (b). (From Figure 11-2 of SDM F1.2).

A fourth set of zones that strikes NS and is vertical or steeply dipping has also been recognised. However, only one local minor zone with a medium confidence of existence and a subordinate number of zones with a low confidence of existence have been included

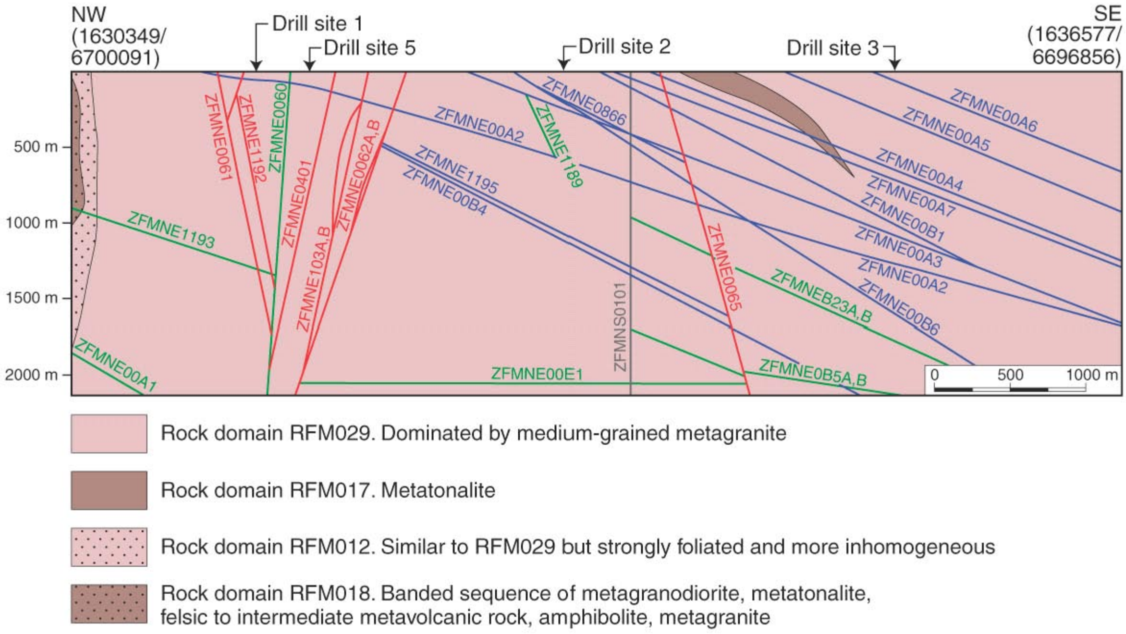

Figure 3-4. *NW-SE cross-section. The zones coloured in red shades are vertical and steeply dipping zones with high confidence, the zones coloured in blue shades are gently dipping zones with high confidence, the zones coloured in green shades are medium confidence zones irrespective of their dip, and the zone coloured in a grey shade is a vertical zone with low confidence (Figure 11-3 of SDM F1.2).*

in model version 1.2. Relative to the other three sets, there is a limited number of such zones and a higher degree of uncertainty concerning the existence of this set of deformation zones.

The following more significant uncertainties, see section 5.4.4 of SDM F1.2, remain following the development of the deterministic deformation zone models:

- The presence of undetected deformation zones cannot be ruled out since there is a strong focus in the geological programme on indirect data in the initial site investigation stage. However, the larger deformation zones (> 3 km) are probably already found, especially inside the target area. Furthermore, the alternative model, with its stochastic components is judged a good illustration of the uncertainty of existence of deformation zones outside the target area.
- The character of features that are represented based on inferred lineaments since various geological processes can explain the formation of a lineament. For this reason, an alternative model is set up, see previous bullet.
- Continuity, dip and thickness of deformation zones interpreted with the help of linked lineaments are uncertain. There are poor constraints on the termination of a linked lineament upon which the length of a deformation zone is partly or entirely based. For down-dip extension, the conceptual model relating depth to length of lineament is uncertain. For dip and thickness, there are restricted amount of data. However, in the "target area", the uncertainty is limited since some percussion and cored boreholes go through some of the deformation zones based, to some extent, on the interpretation of linked lineaments. No such assessment is possible outside the "target area". The uncertainty is provided as ranges for the position, orientation, thickness and length of all the medium and high confidence deformation zones documented in the tables for the properties of deformation zones (see Appendix 3 of SDM F1.2).

- The continuity and thickness of the gently dipping zones that are based, to a large extent, on the seismic reflection data, are uncertain. The uncertainty is provided as ranges for the position, orientation, thickness and length of all the medium and high confidence deformation zones documented in the tables for the properties of deformation zones (see Appendix 3 of SDM F1.2).

The model description of the deformation zones contains information on observed ductile and brittle deformation. Some of the zones are only ductile, with little impact on permeability or potential for future reactivation and of possibly little concern for safety or engineering. However, other ductile deformation zones show signs of later brittle reactivation. From a safety point of view all modelled deformation zones thus needs to be considered, at least until their characteristics are further established.

Also, the upper few tens of metres of the bedrock contain fractures with a large aperture that are more or less parallel to the ground surface. Some of these fractures are filled with glacial sediments. These structures formed or reactivated as a result of stress release in connection with the removal of ice during the last glaciation and/or, at an earlier stage, in connection with the removal of the Phanerozoic sedimentary cover. However, there is no evidence of faulting or major earthquakes since the disappearance of the last inland ice sheet.

Statistical discrete fracture network 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 /La Pointe et al. 2005/ and outlined in section 5.5 of SDM F1.2. The conceptual framework of the model was derived from appropriate statistical testing of initial hypotheses concerning salient aspects of the model geometry and the geological controls on that geometry. These analyses state:

- The DFN model needed to consists of four sub-vertical sets and one sub-horizontal set of fractures. The four sub-vertical sets strike in the same direction as the trend of the structural lineaments, and their size distribution parameters are consistent with the size distribution parameters of the lineaments, suggesting that there are four subvertical sets with sizes varying from centimetres to kilometres. It is not known if the sub-horizontal set of fractures is related to any of the lineament sets. The fracture sets appear to be old, dating back to the early deformational phases prior to 1,700 million years ago. Recent processes, such as deglaciation and crustal rebound, do not appear to be responsible to any significant extent for the observed fracturing.
- The fracture intensity, and the presence or absence of particular sets, vary by rock domain. They also can vary significantly within a specific rock domain. There are sub-domains of relatively constant orientation and intensity on the scale of hundreds of meters within individual rock domains. However, the variations among the subdomains can be quite significant. The geological reasons for the development of these sub-domains are not currently understood.
- The sizes of the fractures belonging to the four sub-vertical sets are relatively well constrained, at least for rock domain RFM029 in which there are abundant data. The size statistics are more poorly known for other domains and, in fact, are not known at all for several rock domains. Particularly important is the possible sizes of the sub-horizontal fractures on which there currently is very limited data.

As discussed in Chapter 5 and Chapter 12 of SDM F1.2 and the supporting document /La Pointe et al. 2005/ there are several uncertainties in the Discrete Fracture Network Model, but the quantification provided in these supporting documents is incomplete. A more extensive estimate of the parameter values for the model, indicating the uncertainties in the scaling exponent in the power low size distribution and in the fracture intensity uncertainties, has been made and will be published in connection to SR-Can.

In the DFN modelling report /La Pointe et al. 2005, e.g. Figure 6-23/ shows that recorded data on trace lengths and frequency allow for a range of slopes, k_r, that all would fit the data. This uncertainty in k_r is explored in the SR-Can data report, as suggested by Figure 3-5, but the values are used already in this PSE. These values are not the same as those listed in /LaPointe et al. 2005, Table 6-12/, since these latter values only are part of defining the envelope of possibilities, see Figure 3-5. A preliminary version of these estimates has been used for this PSE, see section 3.2.6.

The assumption that all lineaments represent brittle deformation zones has a large impact on the *size* and *intensity* distribution and thus on the entire DFN-model. Extrapolating data from surface outcrops to several hundreds of metres depth is subject to considerable uncertainty, and the validity of the DFN cannot be fully addressed until detailed underground fracture mapping, and analyses thereof, has been performed. However, the fracturing pattern was essentially established quite early in geologic history. The oldest fractures are judged to be c. 1.7 Ga old and were formed when the present rock surface was at a few km depth. Experience from the Äspö HRL are that although the intensity of the surface fractures might be augmented by e.g. glacial processes, the relative length distribution, the orientations and the few surviving mineral fillings very well match the fracture array mapped some hundred metres below. Therefore data on outcrop fractures can be used for estimating DFN parameters, especially for obtaining the length distributions.

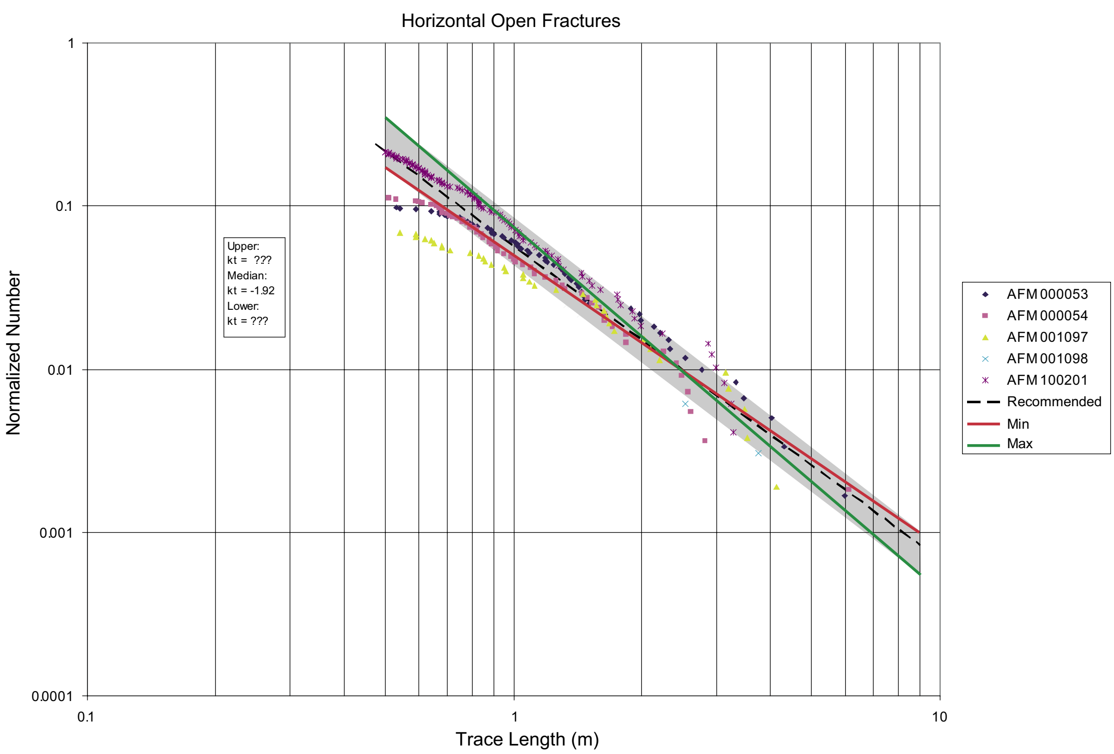

***Figure 3-5.** Estimate of uncertainty in k_r within envelope of recorded trace length data.*

A possibly more problematic issue is the conceptual uncertainty regarding whether lineaments and fractures from outcrop mapping belong to the same statistical size distribution. Interpolation between these data sets is necessary to bridge the gap in data in the range 25 m to 1,000 m, over which there are few direct measurements. Also, the size distribution of sub-horizontal fractures is uncertain due to poor information, as such fractures are not well represented at outcrop as a consequence to their orientation. At the current stage these uncertainties in the DFN-model are only partly quantified by /La Pointe et al. 2005/

The *spatial model* of fracturing with depth is uncertain since the orientation of fractures and the intensity changes with depth and alternative conceptual models can be proposed i.e. by considering fracturing to be related to lithology, proximity to deformation zones or just depth. The uncertainties are quantified as range of intensities, based on fracture frequency (P_{10}) in different borehole sections and fracture trace density (P_{21}) on outcrops, see section 5.5 in SDM F1.2. This section also notes that an alternative spatial model could be to divide rock domain 29 into different subdomains, with the near-surface rock as one subdomain, and at further depth separate the rock above and below the deformation zone ZFMNE00A2 into different subdomains. In fact, such alternatives are developed within the hydrogeological modelling in order to match the fracturing with the observed strong variation in hydraulic properties of the rock. However, the spatial distribution of this variation has not been fully established.

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 Forsmark area /SKB, 2005b/ 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 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. Repository panels are permitted to be constructed across these shorter zones and with a margin of construction applied for the individual deposition holes. Figure 3-6 shows resulting respect distances, indicating potentially available deposition areas, at the –400 m level within the target area. Both high and medium confidence zones are considered. There is little difference in the available area between the –400 m and the –500 m level. All deposition areas are located within rock domain RFM029 and between the gently dipping deformation zones ZFMNE1193 and ZFMNE00A2, see Figure 3-4.

The potential repository layouts presented for the Forsmark area 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 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.

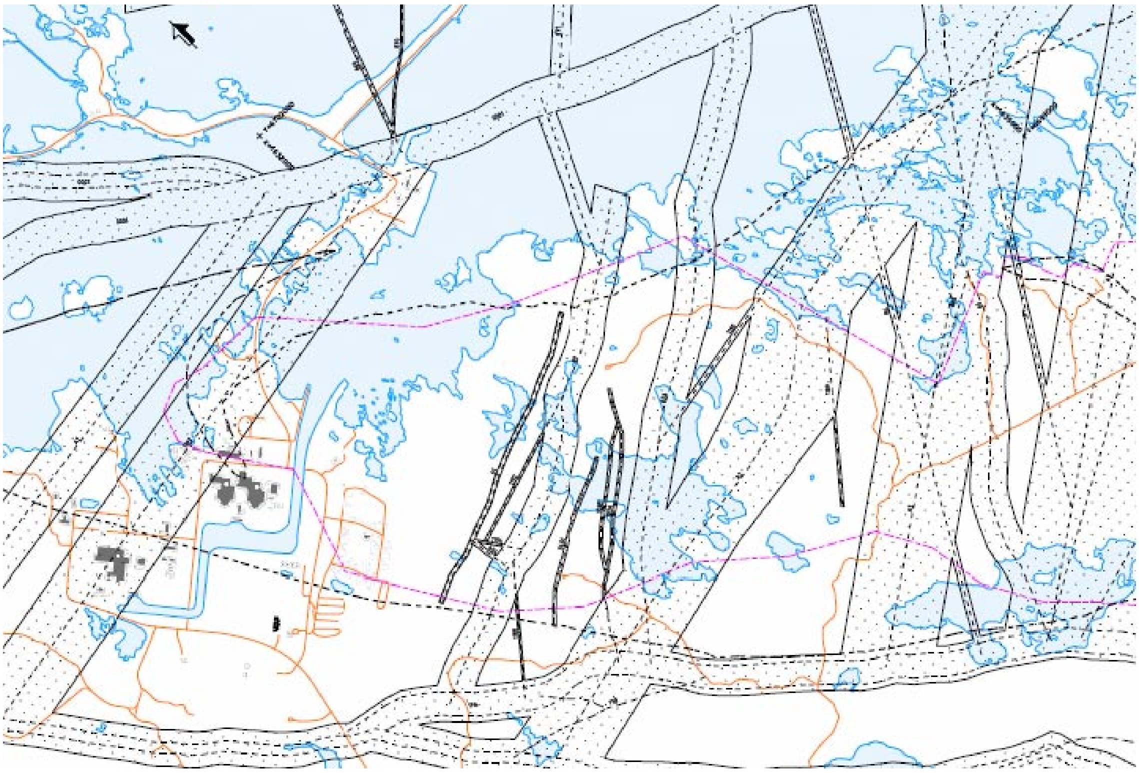

Figure 3-6. *Respect distances from the large (> 3,000 m) high and medium confidence deformation zones at the –400 m level. (From /SKB, 2005b/).*

Using this information, the modelled thermal properties and the assessment of degree of utilisation the layout D1 design work for the Forsmark area /SKB, 2005b/ presents potential layouts adapted to the respect distances. Figure 3-7 shows a potential layout at the –400 m level. At this level the degree of utilisation, which depends on rock stability and potential water problems, see sections 3.2.6 and 3.3.3 below, is estimated to be 89 percent. Layouts at the –500 m level have also been developed and those need about the same area, but the degree of utilisation decreases to 86 percent, due to expected problems of rock spalling in deposition holes.

The layout D1 design work for the Forsmark area /SKB, 2005b/ 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 F1.2, increasing the margin for construction to the deformation zones shorter than 3 km, varying the distances between deposition holes and deposition tunnels and varying the maximum length of deposition tunnels (from 300 m to 600 m). Of these changes, the size of deformation zones, the uncertainty in dip, the degree of utilisation and the distance between deposition holes have the largest influence. It is generally found that there is sufficient space, with margin to host a repository within the target area. Furthermore, it should also be remembered that the target area only is a subset of the Forsmark candidate area.

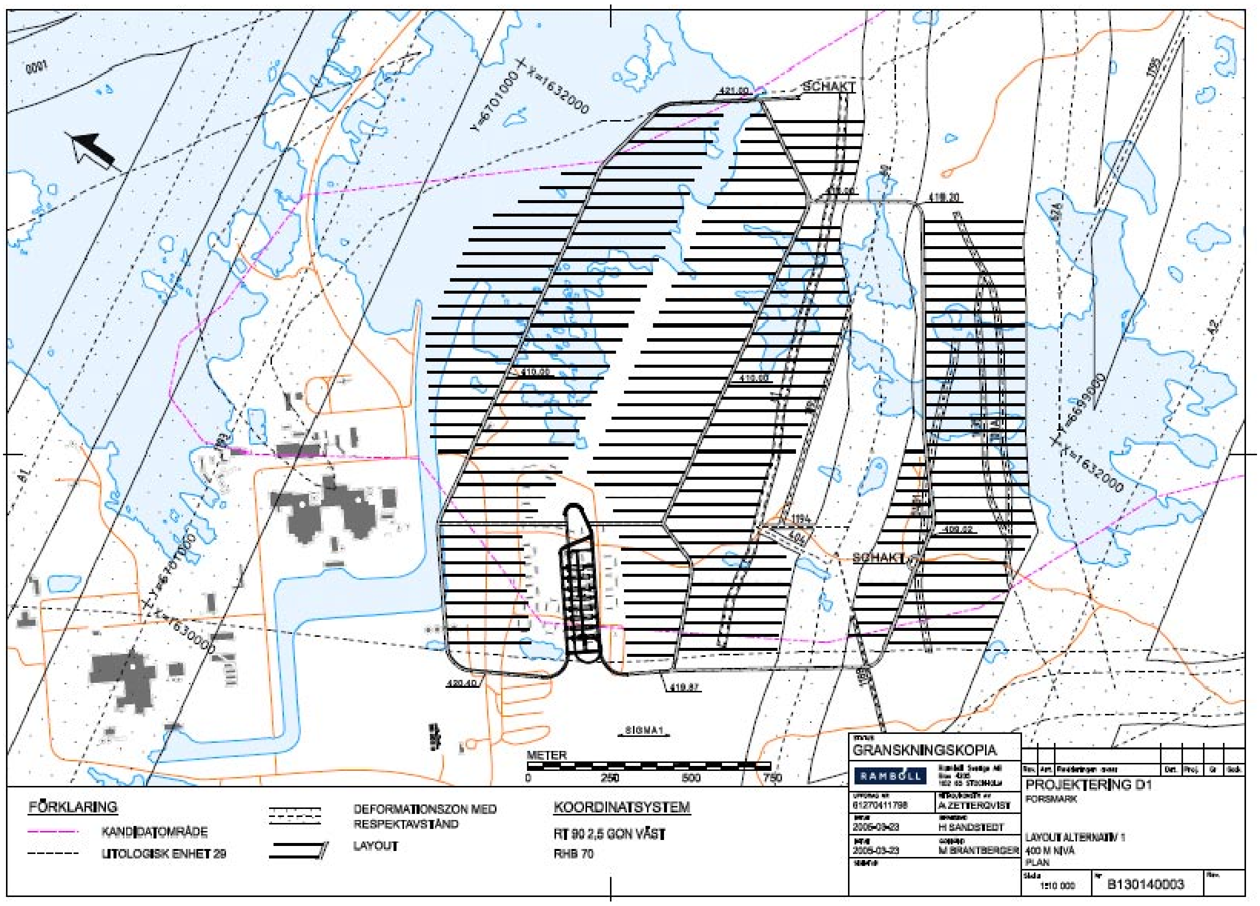

Figure 3-7. *Potential Layout at the –400 m level. (From /SKB, 2005b/).*

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 post-glacial faulting would only be an issue in deposition holes intersected by fractures (or deformation zones) with radii exceeding 50 m (for a 100 m respect distance) or 100 m (for a 200 m respect distance). At least 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 holes is adopted, what would be the impact on the degree of utilisation, given that the design rule would need to over predict whether a deposition hole is intersected by a fracture larger than the critical size? The answer to this question has more implications for design.
- If a design rule is applied for discarding canister, 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 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. From the point of view of long-term safety, the issue is to determine the risk of *deposited canisters actually being intersected by discriminating fractures*. 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, ε, of radius larger than 50 m is about 2.7 percent using best estimate parameter values from the geological DFN model of rock domain RFM029, additional data given in Table 3-4 and the method referred to above. It is emphasized that ε is the expected fraction of canisters intersected by discriminating fractures if no deposition positions are discarded. In reality, a substantial part of these positions are expected to be found and not utilised.

The layout has been 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 50 m (minimum fracture radius in Table 3-4). Deposition holes positioned more than 200 m from any deformation zone are discriminated if they are intersected by fractures with radii exceeding 100 m, see /Munier and Hökmark, 2004 / 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 0.86 percent.

The fractures of interest, from this perspective, are those that are assumed not to be readily detectable in tunnels. In the present calculation, all fractures with radii exceeding 250 m (maximum fracture radius in Table 3-4) are assumed to be readily observable. Increasing the maximum fracture radius to 500 m increases the number of intersected positions by roughly twenty five 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.

Table 3-4. Data, additional to the Geo 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	100 m
Maximum fracture radius (larger fractures assumed trivially observable and thus avoided)	250 m

Sensitivity analyses and variations between rock domains

The result is sensitive to uncertainties in k_r, the exponent of the power-law distribution of fracture sizes in the DFN model. This is illustrated in Figure 3-8, where the leftmost bar in the figure shows the best estimate result of 2.7 percent along with results obtained with upper and lower estimates of the k_r parameter for rock domain RFM029, see Figure 3-5.

The subsequent five bars show the corresponding results for each of the five fracture sets in the DFN model of rock domain RFM029. Results for rock domains 12, 17 and 18 are also shown in the figure, as are the effects of taking another critical parameter, the minimum fracture radius contributing to the DFN description, r_0, from either of the two DFN models developed for the hydrological modelling of the Forsmark site.

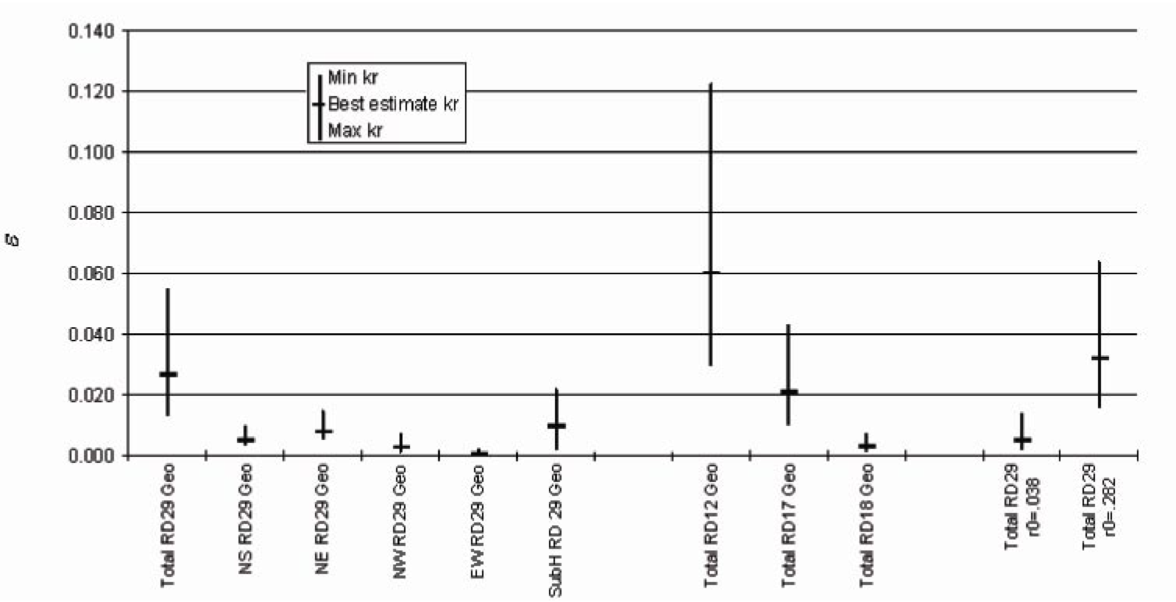

Figure 3-8. *Fraction of canisters intersected by discriminating fractures, ε. Each case shows results with best estimate, max and min values of the k_r-parameter.*

The sensitivity to e.g. details of the orientation distribution of fractures is considerably less pronounced, see further /Hedin, 2005/. The sensitivity to k_r reflects the fact that the power-law size distributions cover a large span of fracture radii in the calculations. However, observations are essentially only available on the metre to tens of metre scale and on the scale of 1,000 m and larger. Observations in the size interval that causes the discriminating fracture intersections in the calculations cited above, i.e. one hundred to several hundred metres, are scarce. It is, therefore, desirable to increase the confidence in the characteristics of this interval of the size distributions.

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 discarded. In reality, most features with radius larger than 50 m are not single fractures, but rather minor deformation zones. This means that many of the too large features would be visible directly in any potential deposition hole. Furthermore, 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.

One of the objectives with the design phase D1 is to determine whether the deep repository can be accommodated within the studied site. The procedure is described in the design premises /SKB, 2004c/. In order not to overestimate the degree-of-utilisation it is prescribed that the degree of utilisation is calculated based on that deposition hole positions are rejected if a fracture exceeding the critical radius would occur within 2 m from a deposition hole. This can be calculated using an effective radius of 2.875 m and an effective height of 10 m for the deposition holes. Furthermore, it is also considered that fractures may have a certain width. This cautious approach accounts for the fact that large fractures (or deformation zones) are likely to be detected by observations through bore holes and in parallel tunnels in the deposition area.

Applying this rule results in around 15.5 percent discarded canister positions, using the method described by /Hedin, 2005/, the best estimate Forsmark 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 with respect distance. For positions farther away, where only fractures larger than 100 m radius need to be avoided, the corresponding figure is 6.0 percent.

The percentage of discarded canister positions, calculated in this way, is much higher than the 2.7 (or 0.86) 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 extended 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/.

It should also be noted that the percentage of discarded positions calculated in this way is larger than the percentage assumed in the design work /SKB, 2005b/, but lies within the ranges considered in the sensitivity analyses carried out within the design work.

3.2.7 Safety implications

The previous sections show that the Forsmark candidate area 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 candidate area does not have any ore potential. 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 target area, i.e. a part of the candidate area, while meeting the required respect distances to the deformation zones and assuming a low degree of utilisation.
- 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 50 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 target area would be helpful to confirm the size and define the location of the suitable deposition volumes. The additional data to be collected and the subsequent evaluation, as suggested in SDM F1.2 appear appropriate for this purpose.

- There is substantial uncertainty in the DFN-model. Efforts need to be spent on reducing these uncertainties. During the Site Investigation Phase this can partly be achieved by acquiring more data, as further discussed in Chapters 12 and 13 of SDM F1.2, but there is a limit on the degree to which these uncertainties can be reduced using only surface based information.
- 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. the k_r parameter in the power-law distribution and further efforts should be spent on providing good support for the possible range of this parameter. 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 have to be adapted to the learning curve during tunnelling, both in the aspect of identify any site specific signature of long fractures/small deformation zones, hydraulic indications of such zones as well as to incorporating this into the training of geologists for the required field works 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. 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 would 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 is *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 for Swedish bedrock.

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 the rock mechanics issues if the strength of the rocks deviates from typical values in 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 making a constructability forecast. Good constructability is of course advantageous.

There is no requirement on the coefficient of thermal expansion, but the SKB criteria considered whether an inhomogeneous expansion could impair the stability of deposition holes. Therefore, there is 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, but rather 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 F1.2, Chapter 6, the stress state in rock domain RFM029 at Forsmark can be estimated as is shown in Figure 3-9 and Table 3-5. The state of stress is estimated based on overcoring and hydro-fracturing results obtained in boreholes KFM01A, KFM01B, KFM02A and KFM04A and from old overcoring measurements in a borehole drilled during the construction of the nuclear power plants (borehole DBT-1). Furthermore, the data have also been assessed in relation to the regional stress state around Forsmark (Finnsjön, Stockholm, Björkö, Olkiluoto). The influence of the deformation zones and their kinematics on the stress field at Forsmark has been analysed by means of numerical models and new studies have also been carried out to improve the understanding of the phenomena of micro-cracking and core disking.

The following basic hypotheses are made for the state of stress at the Forsmark regional model area:

- The vertical stress (σ_v) is due only to the weight of the overburden.
- The maximum horizontal stress (σ_H) trends NW-SE, sub-parallel to the plate-ridge push and to the regional deformation zones at the site. The magnitude is significantly higher, at least at some 200–500 m depth, compared with other sites in Scandinavia.
- The minimum horizontal stress (σ_h) seems to be in the range of what is commonly found in Scandinavia at 200–500 m depth, but the data exhibit large scatter.

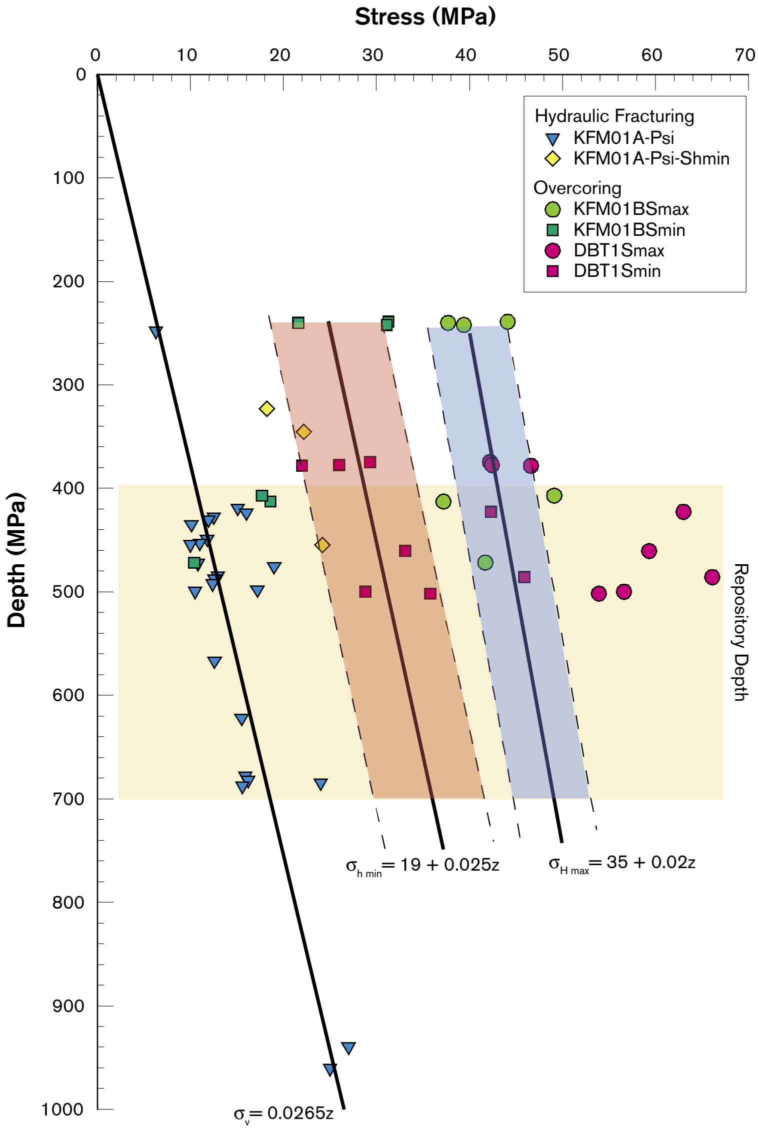

Figure 3-9. *Stress measurements and stress modelling results for RFM029 at Forsmark (after /Sjöberg et al. 2005/). (Figure 6-16 in SDM F1.2).*

Table 3-5. Estimated maximum stresses as a function of depth (in metres) for Rock Domain RFM029 at Forsmark. The equations are valid for a depth between 350 and 650 m. (Table 6-10 in SDM F1.2). Average orientation of the maximum horizontal stress ($\sigma_{H)}$ is 140°).

Magnitude and orientation	Min [MPa]	Average [MPa]	Max [MPa]
Vertical stress (σ_v)	0.0260 z	0.0265 z	0.0270 z
Maximum horizontal stress (σ_H)	Average–10%	35+0.020 z	Average+10%
Minimum horizontal stress (σ_h)	Average–20%	19+0.025 z	Average+20%

* z is the depth from the ground surface in metres (350 < z < 650 m).

The geomechanical and stress data also show that the upper crust, down to about 100–200 m depth, exhibits a more varying stress state characterised by local changes in magnitude and orientation.

The rock stress magnitudes and their spatial distributions are uncertain, since measured stresses are at the upper limit of applicability of the measurement methods. The uncertainty on the mean values of the maximum and minimum horizontal stress magnitude for depths between 350 and 650 m in rock domain RFM029 are also provided in Table 3-5. The intervals take into account the spatial variability of the stress component in the rock volume considered.

It is evident from Table 3-5 and Figure 3-9 that there is good confidence in the vertical stress. Estimating the horizontal stress is more challenging because the stress data are compiled from boreholes that are located hundreds of metres apart from each other. For example, borehole DBT-1, for which the highest stress magnitudes arise as shown in Figure 3-9, is located north of the candidate area (near the power plant) in a local geology that differs from the geology found in KFM01A and KFM01B. These spatial differences have been factored into the stress gradients given in Table 3-5.

Furthermore, all the stress measurement methods suffer from different kinds of uncertainties that often derive from the assumptions behind the processing technique. These uncertainties are considered in the stress estimation, as further discussed in section 6.4.5 of SDM F1.2.

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 F1.2, Chapter 6, the two rock types tested in the laboratory (granite to granodiorite and tonalite) can be assumed to be the predominant rock types in rock domains RFM012 and RFM029 (granite to granodiorite) and rock domain RFM017 (tonalite to granodiorite), respectively. The estimated properties of different rock types in the volume are provided in Table 3-6. Rock domain RFM018 is composed of a mixture of several rock types. It seems reasonable to assume that the properties of the rock types in the table can be used to define the upper and lower boundaries of the properties of the intact rock in rock domain RFM018.

The properties are obtained by means of internationally established standard methods and procedures (e.g. ISRM Suggested Methods) and the uncertainty is considered to be represented by the scatter of the experimental results. Moreover, it is also assumed that the rock samples are representative of the intact rock inside each rock domain. Table 3-6 lists the assessed spatial variability and uncertainty, based on data from different samples and testing laboratories. There is also confidence in the data since they compare well with old data from the repository for reactor waste, SFR, located just northeast of the candidate area.

Table 3-6. Estimated rock mechanics properties of the intact rock for the main rock types in the Forsmark local model volume. The mean value and the standard deviation of the properties are given with the truncation intervals for the normal distribution. (From Table 6-5 of SDM F1.2).

Parameter for intact rock (drillcore scale)	Intact rock in RFM029 and RFM012		Intact rock in RFM017	
	Granite to granodiorite		Tonalite	
	Mean/Standard deviation	Truncation interval: Min and Max	Mean/Standard deviation	Truncation interval: Min and Max
Uniaxial compressive strength, UCS	225/22 MPa	180–270 MPa	156/13 MPa	130–180 MPa
Young's modulus, E	76/3 GPa	70–82 GPa	72/3 GPa	65–80 GPa
Poisson's ratio, ν	0.24/0.04	0.15–0.30	0.27/0.04	0.20–0.35
Tensile strength, TS	13/2 MPa	10–17 MPa	15/1.5 MPa	13–18 MPa
Coulomb's cohesion, c' [1) 2)]	28/3 MPa	22–34 MPa	30/2.5 MPa	25–35 MPa
Coulomb's friction angle, ϕ' [1) 2)]	60°/0.4°	59°–61°	47°/0.2°	46°–48°
Crack initiation stress, σ_{ci}	120/20 MPa	85–190 MPa	82/9 MPa	70–95 MPa

[1)] The cohesion and friction angle according to the Coulomb's Criterion should be correlated so that the minimum value of the friction angle is combined with the minimum value of the cohesion, the mean with the mean, and maximum with maximum, respectively.

[2)] The cohesion and friction angle are determined for a confinement stress between 0 and 15 MPa.

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 F1.2 the coefficient of thermal expansion has been measured on samples from three different boreholes, KFM01A, KFM02A and KFM03A, in the Forsmark area /Åkesson, 2004abc; Carlsson, 2004; Liedberg, 2004/. The mean value of measured thermal expansion varies for the different rock types between $7.2 \cdot 10^{-6}$ and $8.0 \cdot 10^{-6}$ m/(m·K). For the dominant rock type granite (101057) in domains RFM029 and RFM012, a mean value of the thermal expansion coefficient is suggested as $7.7 \cdot 10^{-6}$ m/(m·K). The standard deviation in the data is about $2 \cdot 10^{-6}$.

3.3.3 Mechanical stability during construction and operation

The layout D1 design work for the Forsmark area /SKB, 2005b/ 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/, but additional considerations are taken into account.

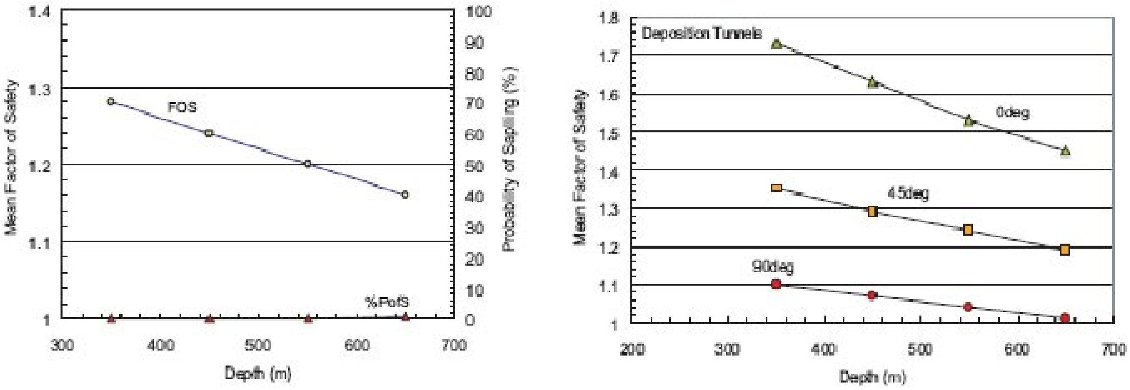

Figure 3-10. *Spalling instability for deposition holes (left) and for deposition tunnels (right). (From /Martin, 2005/).*

/Martin, 2005/ draws the following conclusions, see also Figure 3-10:

- At a depth of 650 m the probability of spalling is less than 1 percent. Hence these results suggest that spalling will not be encountered along the deposition holes, regardless of the repository depth. However, it should be noted that below a depth of 500 m there is less confidence in the in situ stress magnitudes used in the analysis. Furthermore, the analysis 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 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.
- The risk for spalling in the deposition tunnels oriented perpendicular to the maximum horizontal stress increases significantly below a repository depth of 450 m.This risk is eliminated at all repository depths if the deposition tunnels are oriented parallel to the maximum horizontal stress.
- The central area of the repository will utilize a series of tunnels with varying cross sections. These tunnels should be oriented parallel to the maximum horizontal stress to minimize the risk of spalling.

The layout D1 design work for the Forsmark area /SKB, 2005b/ and /Martin, 2005/ thus suggests that the deposition tunnel directions should be parallel with the main principal stress orientation. Further, the design analysis cautiously suggests a 7 percent loss of canister positions at 400 m depth and 10 percent loss at 500 m depth, despite the more promising conclusions drawn by /Martin, 2005/.

3.3.4 Safety implications

The above sections show that the Forsmark area meets all the rock mechanics requirements:

- The rock mechanics properties of the intact rock lie within ranges typical of Fennoscandian crystalline rock.
- The stress levels are comparatively high. For a depth of 500 m, an average maximum horizontal stress of about 45 MPa is estimated. However, this estimate is considered uncertain. This implies that attention has to be given to possible construction and stability problems, especially if the repository were to be located at great depth.

- At less than 400 m depth the probability for spalling in the vertical deposition holes is judged to be very small, and still at a depth of 650 m the probability of spalling is less than 1 percent. Hence these results suggest that spalling will not be encountered along the deposition holes, regardless of the repository depth, but there are uncertainties in the analyses and in confidence in stress below 500 m is lower.
- The risk for spalling in deposition tunnels oriented perpendicular to the maximum horizontal stress increases significantly below a repository depth of 450 m. This risk is eliminated at all repository depths if the deposition tunnels are oriented parallel to the maximum horizontal stress.
- Considering the high stress levels, 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.

Considering the high and uncertain stress levels, further reductions in the uncertainties in stress and rock mechanics properties are needed. The additional data suggested in Chapter 13 of SDM F1.2 appear appropriate to fill these needs. Also, the issue of spalling due to the thermal load may require 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 on the canister and in the buffer may affect the properties of these important barriers. However, the temperature level 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 concern 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.

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

The premises for temperature restrictions on the canister surface are essentially still valid, as discussed in Chapter 6 of SR Can Interim Report /SKB, 2004a/. There, it is stated that the temperature at the canister surface should be restricted so that at the time when water comes into contact with the canister, boiling will not occur. Boiling may result in salt deposits on the canister surface and such deposits could cause corrosion in a way that is difficult to analyse quantitatively. Therefore, the temperature at the canister surface at water contact should be less than 100°C. This is essentially achieved by limiting the initial activity of the fuel in each canister and by adapting the layout of the repository. However, recent experiences from the Äspö Hard Rock Laboratory suggests i) that salt deposits on the canister surface will occur both above and below the boiling point and ii) that these are not of a nature that would compromise long-term safety, i.e. not enhancing corrosion. The thermal criterion for the canister will therefore be revisited in the final reporting of the SR-Can assessment. It seems likely that, the requirement that boiling should not occur near the canister surface will be seen as a preference, but not a requirement directly related to long-term safety.

No credit is taken for the effect of increased hydrostatic pressure on the boiling point, since it can not be guaranteed that this will have developed when the peak temperature occurs. Nor is any credit taken for an increased boiling point due to solutes in the contacting water, since no minimum solute concentration can be guaranteed. The impact of the increase in air pressure, due to the low elevation in the repository, is also pessimistically neglected.

Also, the buffer temperature should not exceed 100°C in order to limit chemical alterations /SKB, 2004b/. The peak buffer temperature will, however, always be lower than the peak canister temperature, so that this criterion is automatically fulfilled if the criterion on canister surface temperature is fulfilled, with the possible exception of canister surface temperatures exceeding 100°C prior to water contact.

3.4.2 Thermal properties and initial temperature

Thermal conductivity and heat capacity

As further explained in Chapter 7 of SDM F1.2 the thermal conductivity at canister scale is modelled using various approaches. The resulting mean thermal conductivity is 3.55 W/(m·K) in RFM029 and 3.46 W/(m·K) in RFM012, see Table 3-7. The standard deviation varies according to the scale considered. At the canister scale it is estimated to range from 0.22 to 0.28 W/(m·K). The lower confidence limit[2], taking account of the spatial variation at the canister scale, is 2.9 W/(m·K) both in RFM029 and in RFM012. There is a temperature dependence with a decrease in thermal conductivity of about 10 percent per 100°C increase in temperature for the dominant rock types. There is limited variation in heat capacity with a mean value of 2.17 MJ/(m^3·K) and a standard deviation of about 0.16 MJ/(m^3·K), see Table 7-15 of SDM F1.2.

Uncertainty in thermal conductivity occurs at different scales ranging from uncertainty in upscaling laboratory size data to larger (e.g. canister) scales, spatial variability within rock types and rock type variability within rock domains. Anisotropy is also suggested in the data, but the interpretation is uncertain; and it may also be overestimated at the small scale, in case the lineation/foliation is not continuous in larger samples.

[2] As noted in Chapter 7 SDM F1.2 it is not possible to fit a normal distribution to the thermal data. Confidence limits could thus not be estimated from the mean and standard deviation. The confidence limits are instead estimated directly from the data using an averaging technique that possibly underestimates the variability.

Table 3-7. Mean value, standard deviation and two-sided 99 percent confidence intervals of thermal conductivity (W/(m·K)) in rock domains 29 and 12 at canister scale. The values are valid at 20°C. At higher temperatures the thermal conductivity for the dominating rock type (granite) decreases by about 10 percent per 100°C (Table 7-13 in SDM F1.2).

Domain	Mean	St. dev.	Lower confidence limit	Upper confidence limit
RFM029	3.55	0.22	2.9	3.8
RFM012	3.46	0.28	2.9	3.8

Upscaling with the rock domain is uncertain due to uncertainty in the spatial distribution of secondary rock types within the domain. The upscaling, including the anisotropy, depends on the structure, orientation and size distribution of these secondary rock types, and not only on their relative proportions. The uncertainty in thermal conductivity has been quantified as ranges at different scales, but better understanding of the upscaling could possibly allow further variance reduction at the larger scales.

Initial temperature

As further explained in Chapter 7 of SDM F1.2 the *in situ* temperature, or rather the temperature of the borehole fluid, has been measured in five boreholes. The mean of all temperature loggings over a specific depth interval provides a mean of the in situ temperature at 400, 500 and 600 m depth estimated to be 10.6, 11.7 and 12.8°C, respectively, see Table 7-11 of SDM F1.2.

There is an uncertainty in the temperature logging results due to disturbance from the drilling and water movements along the boreholes, although this difference in temperature is relatively small for a specified depth but the influence on the design of a repository may be important. The uncertainty is quantified as a range.

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, 2005b/, 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 criteria for the canister and the buffer are met. 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 3-8 shows the resulting minimum spacing for different depths and for different values of the thermal conductivity. The designed minimum canister spacing is based on a constant value of the thermal conductivity, 40 m separation between deposition tunnels and a heat capacity of 2.08 MJ/(m^3·K). In order to account for the spatial variability of the thermal conductivity, the design formula considers 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 safety margins, with the selected canisters spacing and for the mean thermal conductivity is about 80°C.

Table 3-8. Minimum required distance between deposition holes for different depths and for different mean value of thermal conductivity. (From /SKB, 2005b/).

Depth (m)	In situ temperature °C	Minimum required distance between canisters (m) for different values of thermal conductivity		
		λ = 3.4 W/(mK)	λ = 3.6 W/(mk)	λ = 3.8 W/(mK)
400	10.6	5.5	5.2	4.9
500	11.7	5.6	5.3	5.0

As can be seen from the table the analysis suggests canister spacing in the range 4.9 to 5.6 m. However, given remaining uncertainties and also considering potential construction difficulties with too small canister separation distances, the design work suggest a reference canister spacing set to 6 m.

Complementary 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 individual canisters reaching temperatures above 100°C, some additional calculations based on the thermal properties of the Forsmark site 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 is verified against numerical results. The model 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 F1.2, summarized 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 domain RFM029 (i.e. where the repository would be located) are shown in Table 3-9. The standard deviation of thermal conductivity reflects spatial variability on the canister scale (the relevant scale for peak canister temperature calculations) and measurement uncertainties. Full documentation of this data evaluation will appear in the SR-Can data report, due in 2006.

Table 3-9. Thermal sub-model data for the central case presented in Figure 3-11. Site-specific data are taken from SMD F1.2. 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	400 m
Canister spacing	6 m
Mean value of rock thermal conductivity at 80°C, RFM029	3.34 W/(m·K)
Standard deviation of rock thermal conductivity, RFM029	0.22 W/(m·K)
Rock heat capacity	2.17 MJ/(m³K)
Temperature at repository depth	11°C
Buffer thermal conductivity	1.1 W/(m·K)
Gap buffer/rock	0.03 m
Gap canister/buffer	0.005 m

Figure 3-11 shows the results of the complementary thermal calculation as the thermal evolution at a number of points located on a radius extending horizontally from the canister mid-point along the deposition tunnel. The peak canister surface temperature at the canister mid-height is 90.0°C, for the input data as listed in Table 3-9, 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 10.4°C meaning that the buffer inner temperature is 79.6°C. The corresponding drop across the 30 mm gap between buffer and rock wall is 4.4°C, from 65.0 to 60.6°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 8.1°C rather than the 10.4°C calculated above.

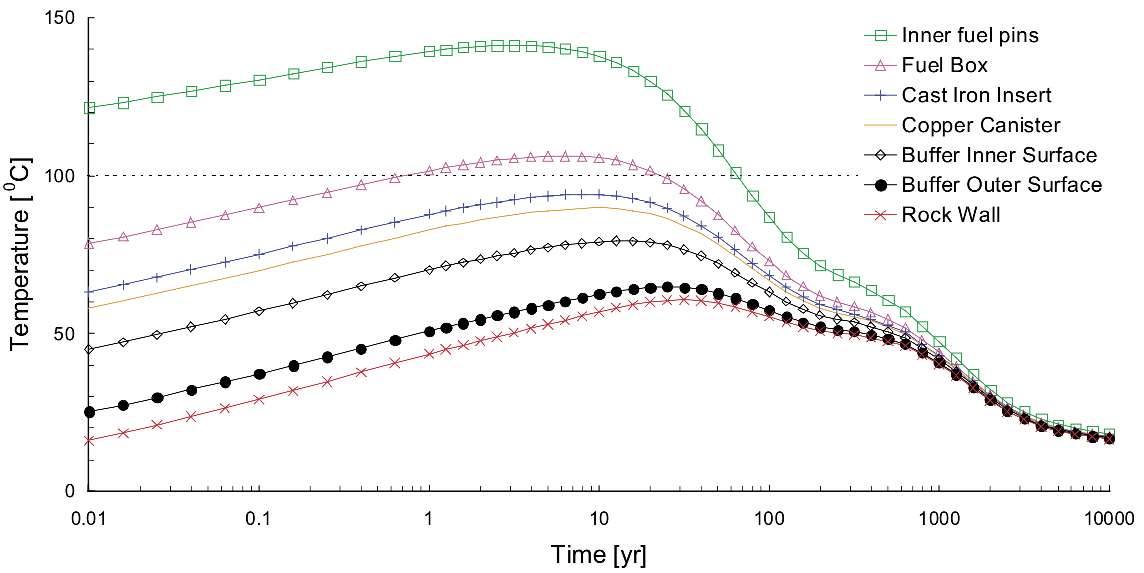

Figure 3-11. *The thermal evolution for a number of points at canister mid-height for data given in Table 3-9.*

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 discussed to mitigate effects of potential spalling at the Forsmark 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 3-12 shows the distribution of canister peak temperature for a probabilistic calculation with all data taken from Table 3-9 where a normal distribution of thermal conductivity with parameters as in the table was assumed, following the recommendation based on the data evaluation by the SR-Can team to be published in the SR-Can data report. This distribution essentially reflects the spatial variability of rock thermal conductivity at the canister scale. The figure shows the result of 5,000 realisations. The highest peak temperature recorded was 100°C. This suggests that the likelihood of exceeding the peak temperature criterion for the canister surface is very low, even when the spatial variability of the rock thermal properties is taken into account.

Figure 3-13 shows how the peak temperatures vary with the centre-to-centre spacing of the canisters. This distance is controlled by the implementer and is thus not uncertain in the same sense as e.g. the rock thermal conductivity discussed above. It is important to carefully select an appropriate spacing, since this determines the overall requirements on space for the deep repository.

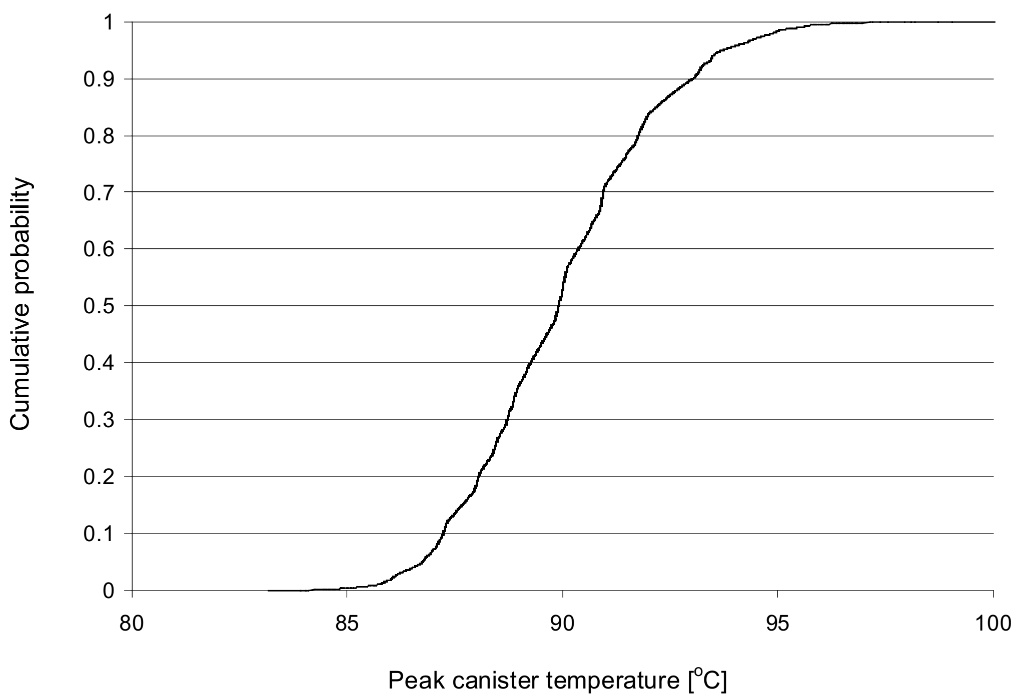

Figure 3-12. *Probabilistic evaluation of the effect on canister peak temperature of variation in rock thermal conductivity. Other data as in Table 3-9.*

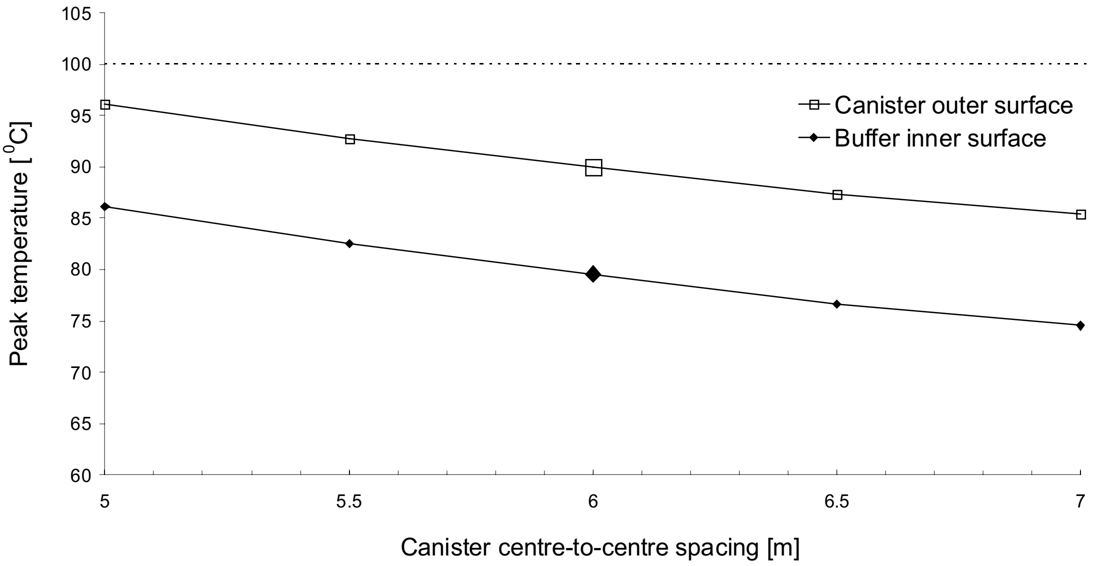

Figure 3-13. *Sensitivity of canister and buffer peak temperatures to the canister centre-to-centre spacing. Other data as in Table 3-9.*

3.4.4 Safety implications

The previous sections show that the Forsmark area meets all thermal *requirements and preferences*.

It is possible to define a layout that ensures that the required temperature conditions on canister and buffer are fulfilled. Furthermore, the designed 6 m spacing appears sufficient. Considering the current estimate of spatial variability of thermal conductivity suggests that essentially all canister positions would result in a maximum temperature below 100°C at the canister surface. In the analysis the highest canister surface peak temperature recorded was 100°C and this would only occur for very few positions.

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. At least locally, it may be possibly to use even shorter canister spacing, or to reduce the spacing between the deposition tunnels in case rock engineering would constrain the minimum canister spacing, but this would require a more detailed understanding of the spatial variability of the thermal properties. Issues worth addressing further include assessing the potential anisotropy of the thermal data and the size distribution of the subordinate rock types within RFM029. The planned data and modelling envisaged in Chapter 12 and 13 in SDM F1.2 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.

3.5 Hydraulic analyses

The hydraulic properties of the rock, i.e. the permeability and conductivity of the fracture systems and the driving forces, control the amount, rate and distribution of the groundwater flow in the rock. 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 permeability (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 to 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 permeability 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 (although hydraulic conductivity alone is insufficient for determining this, see section 3.7.3)[3]. 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 is 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 such low permeability 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, also less transmissive zones would 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. Data on the hydraulic gradient, boundary conditions, or data on recharge/discharge areas primarily are needed for building credible groundwater models. No requirements were set, but rather arbitrarily it was

[3] 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".

suggested that there is an advantage if the local gradient is less than 1 percent at repository level (but no additional advantage if even 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 permeability

As further explained in Chapter 8 of SDM F1.2, 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 the Hydraulic Rock Domains (HRDs) representing the rock mass between the HCDs. The hydraulic properties of the HRDs are modelled as discrete fracture network models, with the geometry taken from the geological discrete fracture network model, but with added hydraulic properties. The models are calibrated against existing hydrogeological borehole data, although it is clear that different conceptual models could be calibrated to the same data.

Transmissivity of the deformation zones

The HCDs in the hydrogeological model are based on the SDM F1.2 regional-scale deformation zones, see section 3.2.4. The HCDs in the hydrogeological model are based on the base case model (BM) version of the Forsmark 1.2 regional-scale structural model. A majority (27) of the 44 deformation zones associated with the BM are hydraulically tested and attributed transmissivity values that are regarded as high confidence information. The estimation of the hydraulic thicknesses of the deformation zones is based on the interpretation of the geological thicknesses of the base case model deformation zones.

A significant observation is made by correlating deformation zone transmissivity to deformation zone dip and depth, see Figure 3-14. The correlation analysis indicates that gently dipping deformation zones generally have greater transmissivities than steeply ones at comparative depths and both gently and steeply dipping deformation zones have much greater transmissivities close to ground surface than at depth.

Although data plotted in Figure 3-14 suggests simple depth dependent trends, it also shows quite a large variation between different deformation zones. 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.

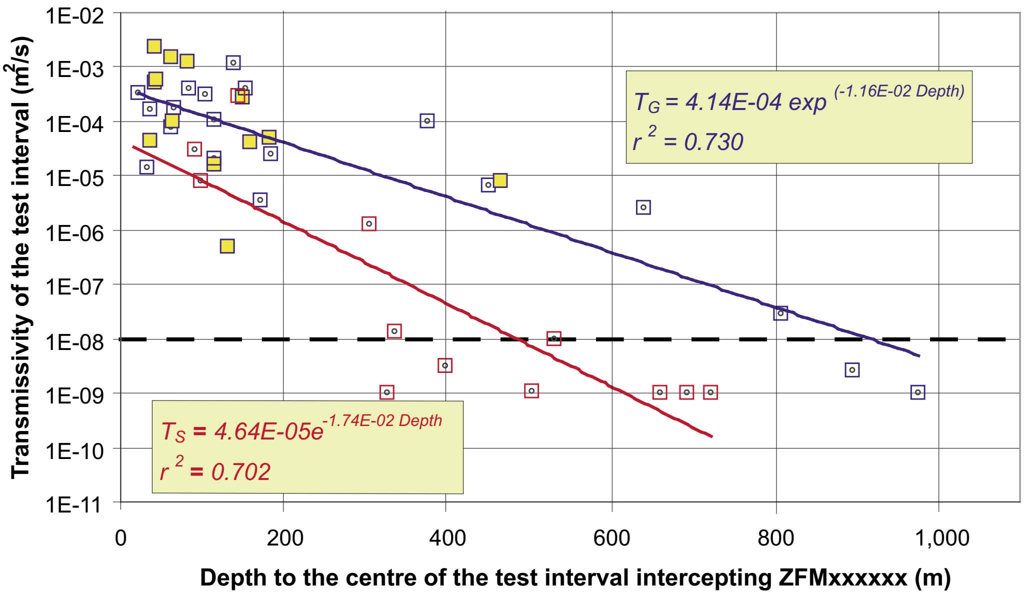

Figure 3-14. *Modelled (lines) and observed (squares) depth dependence of transmissivity in deformation zones. Red squares indicate steeply dipping DZs and blue gently dipping. Blue squares with a white infilling refer to the hydraulic test interpretations associated with ZFMNE00A2 (Figure 8-33 of SDM F1.2).*

The uncertainty in geometry and connectivity of deformation zones motivated the formulation of alternative deformation zone models, as discussed in section 3.2.4. These uncertainties also imply uncertainty as to how these modelled structures relate to structures of hydrogeological significance. Apart from the uncertainty in the geological model, this uncertainty is due to lack of hydrogeological data testing whether there is a hydraulic contact between the rock inside the candidate area and rock outside, e.g. through gently dipping deformation zones. The transmissivity distribution and its spatial variability in deformation zones outside the candidate area are also uncertain, since there are few, if any, hydraulic measurements in these zones. This uncertainty could potentially affect the strength of the hydraulic contact between the rock inside the candidate area and rock outside.

The calibration against hydrogeochemistry data (palaeohydrogeology, see Chapter 8 of SDM F1.2) provides some means of testing the current model. In principle the uncertainty has a fundamental impact on modelling the regional groundwater flow and hydrogeochemical system. In practice, the uncertainty is explored by analysing the sensitivity to the transmissivity distribution in the regional groundwater flow modelling and by testing two alternative models for deformation zones in the regional domain, see Chapter 8 of SDM F1.2. It is there concluded that the flow inside the target area is essentially insensitive to the regional uncertainties treated, whereas the spatial variability of the transmissivity for the zones inside the target area would have an impact on the detailed flow in this area. However, the spatial variability of transmissivity within the zones within the target area does affect the flow there. This spatial variability would eventually need to be handled, see also section 3.5.3 below.

Hydraulic properties of the rock mass

The hydraulic properties of the rock mass are described by means of a hydraulic discrete fracture network model (Hydro-DFN). The analyses were made by two different modelling teams /Follin et al. 2005/ and /Hartley et al. 2005/. Both teams reached very similar conclusion, although there resulting description show slight differences due to the uncertainty and ambiguity of interpreting the data. As further discussed in Chapter 8 and Chapter 12 of SDM F1.2, there are several related uncertainties in the hydraulic properties of the rock mass between the modelled deformation zones. This concerns *division into volumes* of different hydraulic properties, the *connectivity* of the discrete fracture network (DFN), the *transmissivity* distribution in these fractures, *anisotropy* and the *spatial variability in the fractures*.

As discussed in Chapter 8 of SDM F1.2, the hydraulic data from the boreholes strongly suggest that the rock mass, inside rock domain RFM029, should be divided into volumes of different hydraulic properties, see Figure 3-15. Noteworthy is the volume below deformation zone ZFMNE00A2 below about the –360 m level (denoted Volume D or G by the different modelling teams), where there are essentially no measured hydraulic responses in the data. However, since there are few boreholes, the exact division of the different volumes remains to be defined. In particular, it should be noted that although it is likely that most of the repository panels according to the layout would lie within model Volume D(G) it cannot be excluded that some parts will be in the more permeable Volume B(F).

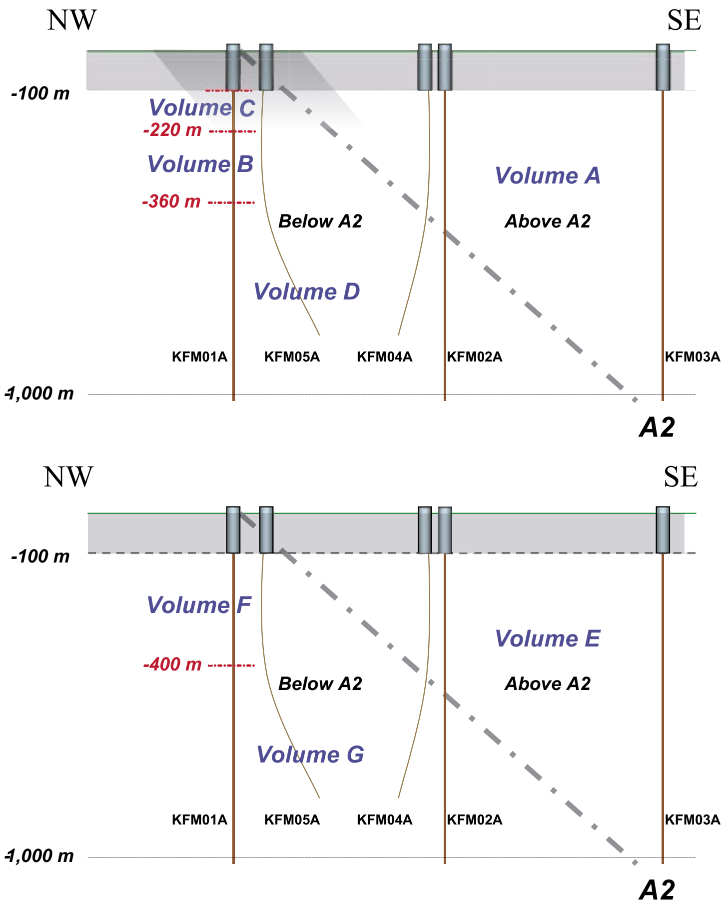

Figure 3-15. *Schematic cross-sections through the tectonic lens illustrating the division of RFM029 into smaller volumes by two modelling teams. The upper model was treated by /Follin et al. 2005/ and the lower by /Hartley et al. 2005/. The difference between the two cross-sections concerns the division of Volume F into Volumes B and C mainly. Thus, Volumes A and E may be considered equivalent as may Volumes D and G, respectively. Volume C is the most conductive, whereas Volume D (G) has almost no measurable inflows according to the data available for Forsmark 1.2. (Figure 8-36 in SDM F1.2).*

Table 3-10 presents the basic fracture frequency data outside the deformation zones used in the analysis carried out by /Follin et al. 2005/. N_{CAL} is the number of potentially flowing Open and Partly Open fractures in each borehole (volume) to be matched in the modelling process and 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). T_{PFLmin} is the smallest transmissivity value measured and may be considered as an estimate of the lower measurement limit T_{lim}. As noted in SDM F1.2 Chapter 8, the lower measurement limit of the PFL method is not a threshold with a fixed magnitude but varies in space depending on the in situ borehole conditions.

The frequency of potentially flowing Open and Partly Open borehole fractures P_{10CAL} varies an order of magnitude between Volumes A–D. In comparison, the P_{10} value of the geological DFN, 67 fractures per hundred metres, falls between the P_{10CAL} values shown in Table 3-10. The value of P_{10PFL} in each volume is at least an order of magnitude lower than the corresponding value of P_{10CAL}. Between Volume C and Volume D, the P_{10PFL} value varies by more than two orders of magnitude.

The hydraulic analysis of the borehole data involves simulations with the DFN models in order to match the flow data measured in the boreholes. However, given the uncertainties in the DFN model, see section 3.2.4, and the scarcity of observed transmissive features in the boreholes, the hydraulic DFN analysis should rather be seen as indicative, where various alternative models are explored. 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".

As already discussed, there is an uncertainty in the intensity of fractures in the size range 100–1,000 m. This is an important issue to be resolved by the geologists. This causes uncertainty in the connectivity of the fracture network, which also affects the assignment of transmissivity distributions to the fractures and the resulting block scale hydraulic conductivities. As assessed in section 8.4.2 of SDM F1.2 the different volumes may be modelled as percolating networks of discrete features, however with quite different hydrogeological DFN properties depending on the assumptions of the intensity of larger fractures in the DFN model. In the low percolating networks it is necessary to set the transmissivity higher in order to match the total measured transmissivity in the different boreholes.

Table 3-10. Basic fracture frequency data outside the deformation zones used in the analysis carried out by /Follin et al. 2005/. Note that Volume B is essentially the same as Volume F and Volume D essentially the same as Volume G in /Hartley et al. 2005/. (Table 8-8 in SDM F1.2).

Borehole	Volume	Interval m	N_{CAL}	P_{10CAL} (100 m)$^{-1}$	N_{PFL}	P_{10PFL} (100 m)$^{-1}$	T_{PFLmin} m^2/s	T_{PFLmax} m^2/s
KFM03A	A	106–994	248	27.9	24	2.7	$1.09 \cdot 10^{-9}$	$3.46 \cdot 10^{-7}$
KFM01A	B	222–363	210	149	11	7.8	$2.71 \cdot 10^{-10}$	$2.22 \cdot 10^{-9}$
KFM01A	C	103–222	304	255	23	19.3	$2.47 \cdot 10^{-10}$	$5.35 \cdot 10^{-8}$
KFM01A	D	367–956	134	22.8	0	< 0.170	$3.62 \cdot 10^{-10}$	$< 3.94 \cdot 10^{-10}$

Of special interest is Volume D (or G). In this volume there is no recorded transmissivity from the hydraulic tests. Depending on the assumptions made on the fracturing, alternative interpretations are possible ranging from a non-percolating fracture network to a poorly percolating fracture network the transmissivities of which are low and below the lower measurement limit of the hydraulic test equipment. In the case of a non-percolating fracture network, the flow and advective transport would essentially only take place in the deterministically modelled deformation zones, possibly with the addition of a very low hydraulic conductivity of the rock matrix itself.

The main assumption is to fully correlate fracture size and transmissivity, setting $\log(T) = b \cdot \log(a \cdot r)$, where r is the fracture radius. However, alternative models, with no correlation, $\log(T) = N(\mu,\sigma)$, or with some correlation, $\log(T) = b \cdot \log(a \cdot r) + N(\mu,\sigma)$, are also applied to the data. These alternatives results in quite different block properties and are possibly less realistic, but cannot be excluded at this point. Concerning the three transmissivity models /Hartley et al. 2005/ concluded that Volume E and Volume F have essentially the same properties. The best match was obtained for the correlated transmissivity model but further fits were produced for the uncorrelated and semi-correlated transmissivity models as well. Table 3-11 summarises the parameter values suggested for the uncorrelated, correlated and semi-correlated transmissivity models in Volumes E–G. From the table it can be noted that the correlated model suggest that a 100 m size fracture has about the same transmissivity (i.e. about 10^{-7} m^2/s) in all volumes, but the intensity of such fractures is more than a factor of 10 less in Volume G, see Table 3-10. For the uncorrelated case the median fracture transmissivity is higher, $3 \cdot 10^{-7}$ m^2/s, but the majority of fractures are much shorter than 100 m.

In apparent contrast to Table 3-11 /Follin et al. 2005/ suggested a much lower transmissivity of the fractures in Volume B and in Volume D. In their analysis a 100 m fracture in Volume B and Volume D would have a transmissivity in the range 10^{-9} m^2/s to 10^{-8} m^2/s (see Figure 8-41 of SDM F1.2). This is most likely due to the fact that Volume B does not include the upper part (Volume C) which is much more conductive.

In SDM F1.2 it is also concluded that the hydrogeological DFN analyses of Volumes D and G are especially uncertain, as there are no flow anomalies in KFM01A. /Follin et al. 2005/ concluded that Volume D becomes non-connected or very poorly connected depending on the used DFN reference size parameter $X_{r(l)}$, however, with all flow below the lower measurement limit. This finding goes well with the sensitivity test conducted by /Hartley et al. 2005/, which suggests that this HRD is close to the percolation threshold.

Whether fractures of different orientations have different transmissivity distributions (i.e. anisotropy) has been analysed by both teams. They only suggest moderate anisotropy, but since there are few data this issue is still uncertain.

Table 3-11. Parameter values suggested by /Hartley et al. 2005/ for the uncorrelated, correlated and semi-correlated transmissivity models in Volumes E–G. (Table 8-10 in SDM F1.2).

Object	Uncorrelated		Correlated		Semi-correlated		
	$\mu_{log(T)}$	$\sigma_{log(T)}$	*a*	*b*	*a*	*b*	$\sigma_{log(T)}$
Volume E	–6.5	0.9	$1.8 \cdot 10^{-9}$	1	$5.3 \cdot 10^{-8}$	0.6	1
Volume F	–6.5	0.9	$1.8 \cdot 10^{-9}$	1	$5.3 \cdot 10^{-8}$	0.6	1
Volume G	–	–	$8.9 \cdot 10^{-10}$	1	–	–	–

Finally, there is likely to be a spatial variability of the transmissivity in the plane of each fracture. This will cause channelling and could also have an impact on the connectivity analysis. This uncertainty is not resolved in the site modelling, but is left for further analysis within safety assessment. A first-order assessment of this is given in section 3.7.3.

Overall, the uncertainty in the hydraulic properties of the rock mass in the target area is at least partly quantified, and especially by considering alternative models of fracture network connectivity, and fracture transmissivity distribution. The uncertainty in the different volumes can at this point be represented by considering a range of properties for each of the different volumes.

Effective values of permeability

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 fractures 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 20 m and 100 m scale, 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.

Table 3-12 and Table 3-13 summarise the results of the block modelling for Volume B and Volume F respectively. In Volume F, as can be seen from Table 3-13, more than 90 percent of the blocks in the 20 m scale have hydraulic conductivity below 10^{-8} m/s for the correlated cases, whereas the percentage is a little lower for the uncorrelated and semi-correlated cases. In Volume B (see Table 3-12) less than 25 percent of all blocks have a conductivity above 10^{-10} m/s, and very few, if any, above 10^{-8} m/s. It should be noted that Volume B, in contrast to Volume F, does not include the more conductive upper parts found in borehole KFM01A.

No block calculations were performed for Volume D (or equivalently Volume G), since there are no data above the measurement limit of the hydraulic testing. This could be interpreted as a hydraulic conductivity below 10^{-11} m/s.

Table 3-12. Block-size effective hydraulic conductivity for Volume B. The block size is 20 m and a correlated transmissivity model was used. The reference size is in metres. The percentiles for the upper bound were estimated by discarding all 20 m grid cell values that were not hydraulically connected in all three directions. The percentiles of the lower bound were estimated by assigning a low hydraulic conductivity value to the non-connected 20 m blocks. $X_{r,min}$ is a parameter in the DFN-model. (Table 8-12 in SDM F1.2).

Corr. *T* model	Scale	$X_{r,min}$	$Log_{10}(K_{eff})$ [m/s]					
			10%	25%	50%	75%	90%	1σ
Upper bound	20	5.64	–10.17	–9.89	**–9.65**	–9.14	–9.03	0.60
Lower bound	20	5.64	–15.58	–14.15	**–12.55**	–10.94	–9.52	2.42

Table 3-13. Effective hydraulic conductivity for correlated, uncorrelated, semi-correlated transmissivity concepts for Volume F. Scale (cell size) and the $X_{r,min}$ truncation size are recorded in metres. In contrast to Volume B, most blocks are percolating. (From /Hartley et al. 2005/ and Table 8-16 in SDM F1.2).

T model	Scale	$X_{r,min}$	$\log_{10}(K_{eff})$ [m/s]					
			10%	25%	50%	75%	90%	(1σ)
Correlated	20	0.28	–10.56	–10.10	**–9.54**	–8.96	–8.48	0.79
Correlated	100	5.64	–10.19	–9.73	**–9.15**	–8.62	–8.31	0.75
Correlated	100	11.30	–10.84	–9.96	**–9.19**	–8.58	–8.28	0.88
Correlated	100	14.10	–11.19	–10.06	**–9.27**	–8.66	–8.32	0.84
Correlated	100	28.20	–23.00	–18.85	**–9.52**	–8.76	–8.83	0.83
Uncorrelated	20	0.28	–9.56	–9.04	**–8.62**	–8.20	–7.94	0.63
Uncorrelated	100	5.64	–10.01	–9.63	**–9.29**	–9.01	–8.77	0.49
Semi–correlated	20	0.28	–10.02	–9.36	**–8.64**	–7.89	–7.49	0.97
Semi–correlated	100	5.64	–10.09	–9.58	**–8.93**	–8.33	–7.85	0.89

Despite the rather high uncertainties in the hydrogeological DFN properties, it is likely that the uncertainty is less in the block properties since they represent averages and since they all are matched with the same hydraulic data. Thus the span given by the different alternative models probably does not underestimate the uncertainty. It should also be noted that the median conductivities suggested by the DFN analysis is close to total borehole section transmissivity divided by the section length. This should not be a surprise, since this has been a calibration target. The added value of the DFN analysis, is that it provides possibilities in estimating the variability around this median value.

3.5.3 Groundwater flow calculations and particle discharge points

Based on the hydraulic property description, the SDM F1.2 also presents transient, density dependent, groundwater flow calculations in an equivalent porous medium representation of a regional scale. The groundwater model is transient and considers density dependent flow, but the flow paths are only 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 target area at 400 m depth, see Figure 3-16. An example of discharge points is shown in Figure 3-17.

The main results from the sensitivity tests are summarised as follows:

- The presence and properties of deformation zones outside RFM029 have little effect on flow and salt transport inside the rock domain since flow is relatively localised. However, a relatively fine grid of no more than 50 m element size is required throughout a local volume that covers the release-area and the calibration boreholes to represent flow and transport due to a large number of gently dipping zones within RFM029.
- HRD block-scale properties of the DFN in RFM029 are more sensitive to the fracture transmissivity model than to the fracture length distribution providing the other fracture parameters are calibrated to the hydraulic data in a consistent methodology.

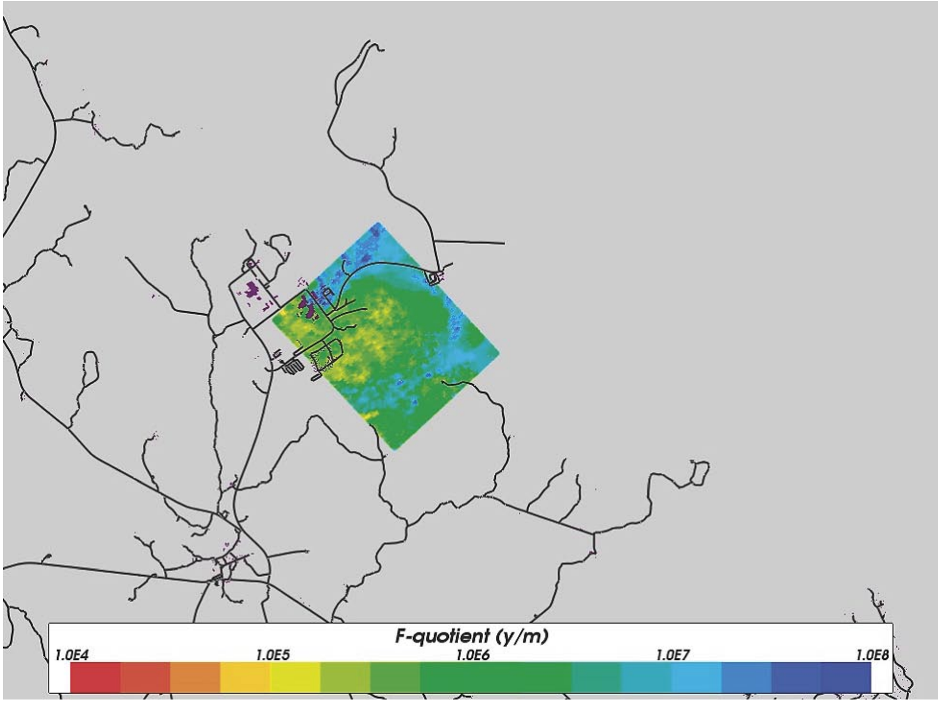

Figure 3-16. *Particle starting locations. Roads are shown in black for context. (From /Hartley et al. 2005/ Figure 9-1).*

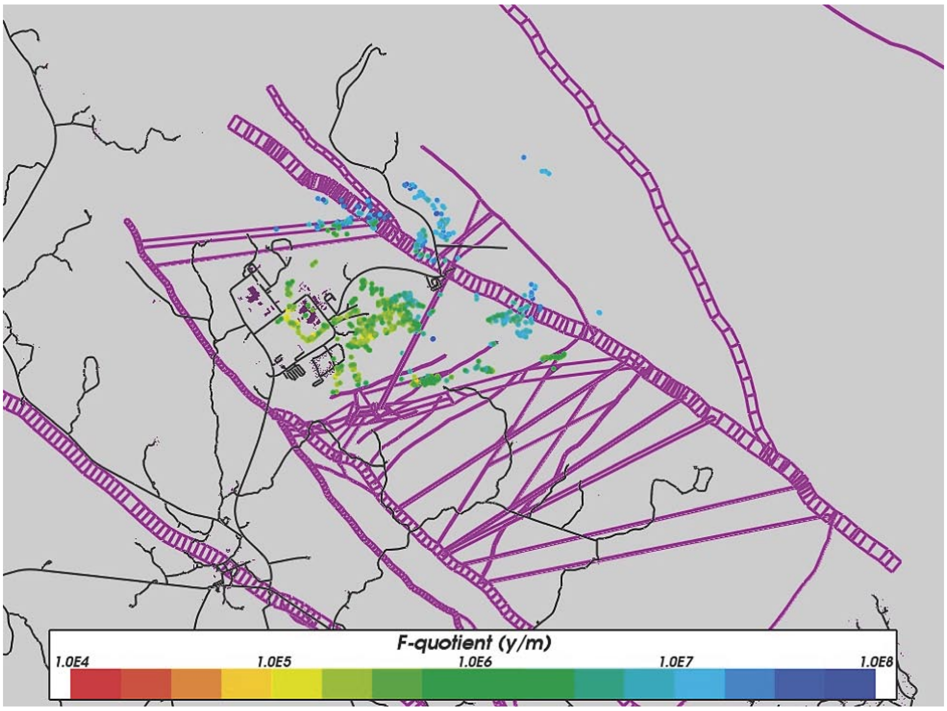

Figure 3-17. *Particle exit locations from one realisation of the Base Case of /Hartley et al. 2005/. A section through the HCD model at z = –100 m is superimposed. Roads are shown in black for context. (From /Hartley et al. 2005/ Figure 9-3).*

- Stochastic variations of the DFN have only a small influence on flow and transport compared with other factors such as the HCD positions and properties. This may justify the sufficiency of relatively few realisations of each HRD case.
- Deformation zone heterogeneity within the candidate area has a clear effect on the local flow distribution.
- The results were not sensitive to the surface property variants considered. However, the model only matched the chloride concentration in the top 100 m of some boreholes. This motivates further investigation of alternative or spatially variable surface properties.

For more detail, see Chapter 8 of SDM F1.2, /Hartley et al. 2005/ and /Follin et al. 2005/.

3.5.4 Safety implications

The previous sections show that the target area at Forsmark meets all hydraulic requirements and preferences. 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, and despite the great uncertainties in the description of the hydraulics of the rock mass, there are essentially no blocks at the 20 m scale with hydraulic conductivity K above 10^{-8} m/s in Volume B or D, i.e. where the repository is judged to be located, see Figure 3-15. In fact, in Volume B there are only about one flowing feature with transmissivity above $3 \cdot 10^{-10}$ m^2/s every 10 m and in Volume D (i.e. below the 360 m level) there is no recorded transmissivity at all. Higher conductivities result if conductivities are estimated based also on the upper part of the boreholes (i.e. including “Volume F”). Depending on the conceptual model, between 5 to 10 percent of all 20 m blocks then have a K above 10^{-8} m/s (see Table 3-13). However, these values are most likely not representative as the upper part of the rock mass appear much more permeable than the deeper parts.
- 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. Such high transmissivity may also be encountered at depth in the gently dipping zones. If there is a need to pass through these zones during the access tunnel construction, the engineering implications will have to be carefully assessed.
- 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, mainly below the sea (see Figure 3-17). The groundwater flow rate is low, indicating low gradients and much below 1 percent at repository level. Furthermore, a sensitivity study shows a very limited impact on these results from various positions of the model boundaries or from the details of the HCD deformation zones in the regional domain. However, the discharge location will be affected by subsequent shore-line displacement and in the future discharge will occur much further to the north east.

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 by expanding this simplistic reasoning and also by exploring results from the regional scale numerical groundwater flow model, but more elaborate evaluation lies outside the scope of the PSE.

Even though the current model indicates very low hydraulic conductivities at potential repository depth, additional site data are needed in order to confirm the extent of the low permeability volumes. The uncertainties in the spatial variation and upscaling of the hydraulic properties warrant further studies. Furthermore, as is elaborated in section 3.7.3, reducing the uncertainty in hydraulics of the fracture network would allow for much less pessimistic handling of the transport resistance of the rock mass. Reducing these uncertainties would involve drilling additional boreholes and carrying out single-hole interference tests (interference tests between nearby cored boreholes are not possible). Such characterisation is planned in the current CSI programme /SKB, 2005c/. More detailed suggestions for how to reduce the uncertainties are given in the SDM F1.2.

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 publishing 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[4], 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 preferences the safety implications need to be specifically assessed.

Additional considerations

The previously set criteria relates only to groundwater at repository depth at the present day. It is important to note that also 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 mineralogy evaluations of the rock types listed in Table 3-3, as well as of the fracture-filling minerals. The redox 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 are not available for the SDM S1.2, 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 F1.2, the complex groundwater evolution and patterns at Forsmark 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.

Four main groundwater types, Types A, B, C and D, are present (Figure 3-18):

- A: Recent to young (0–15 TU) Na-HCO_3 type groundwaters of meteoric origin ($\delta^{18}O$ = ~ –11.7 to –9.5‰ SMOW; δD = ~ –85 to –76‰ SMOW).
- B: Old (~ 13–22 pmC) Na-Ca-Cl(SO_4) type brackish groundwaters of Littorina Sea origin ($\delta^{18}O$ = ~ –11.5 to –8.5‰ SMOW; δD = ~ –85 to –65‰ SMOW); some mixing with present meteoric water and/or cold climate water (glacial origin) is also characteristic.

[4] 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 suggest that [DOC] > 10 mg/L in surface waters.

- C: Saline Na-Ca-Cl type groundwaters, but devoid of a Littorina Sea signature (i.e. low Mg and SO_4), are present at greater depth (KFM03A; 645 m). These probably represents a mixing of deeper saline groundwater (Ca-Na-Cl) and a cold climate glacial water component ($\delta^{18}O$ = –11.6 to –13.6‰ SMOW; δD = –98.5 to –84.3‰ SMOW) which continues to at least 1,000 m depth.
- D: Strongly saline, non-marine Ca-Na-Cl type of groundwater of deep origin is probably dominating at still greater depth (> 1,000 m). At the moment, this is suggested only by field observations during pumping tests.

The shallow Na-HCO_3 (Type A) groundwaters form a distinctive horizon at the centre of the transect in Figure 3-18. It lenses out towards the SE Baltic Coast where discharge of deeper groundwater probably occurs. From Lake Bolundsfjärden to the NW, a less marked horizon is indicated, but data are few. In addition, the influence of the deformation zone A2 on the groundwater chemistry is not clear at this near-surface locality, but may represent some kind of boundary between Type A and the deeper Type B Littorina groundwaters.

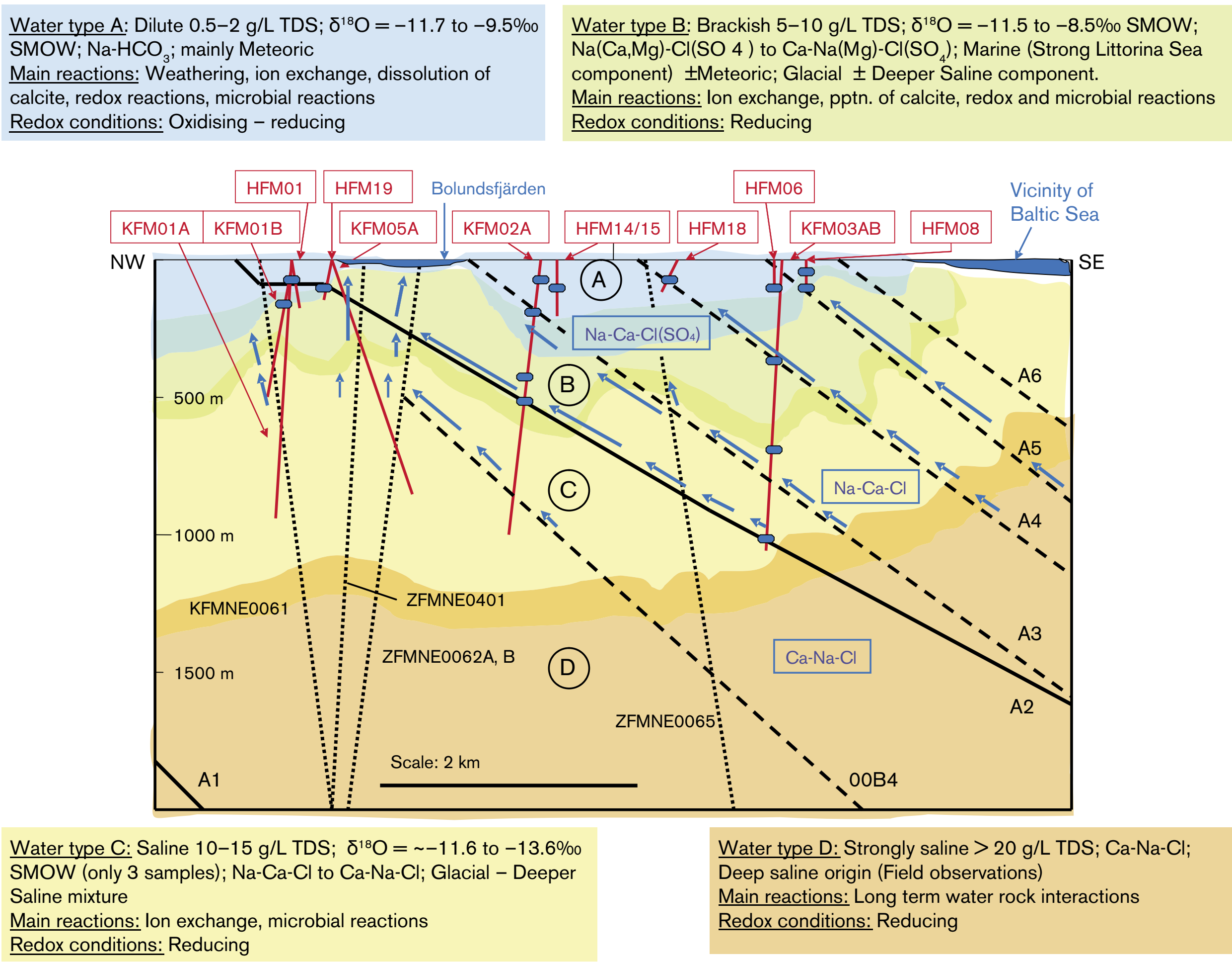

Figure 3-18. *Schematic 2-D cross-section, along the current shoreline, integrating the major structures, the major groundwater flow directions and the variation in groundwater chemistry (Types A–D) from the sampled boreholes (indicated in blue). The blue arrows are estimated groundwater flow directions. (Figure 11-7 in SDM F1.2). Note, this cross-section is essentially perpendicular to the main flow direction.*

Bordering the shallow Na-HCO_3 groundwaters, and extending from close to the surface (near the SE coast) to depths of around 500 m (e.g. along the gently dipping deformation zone A2), are the Type B Littorina Sea groundwaters. The shallow occurrence of Littorina Sea waters is supported by a soil pipe groundwater sample (SFM0023) collected under Lake Bolundsfjärden, which showed elevated content of Mg and SO_4. An explanation for the preservation of Littorina water beneath Lake Bolundsfjärden could be the low permeability of the bottom sediments of the lake, which, together with the flat topography, would limit flushing out of the water from the rock.

The distribution of the deeper, more saline groundwaters is based on few data, but these appear to represent much older groundwaters of deep origin (> 1,000 m) that have undergone mixing with cold climate glacial waters at least down to around 1,000 m depth, but, it should be remembered that the chemical data only is sampled in the highly transmissive deformation zones. Lack of data prohibits a more specific interpretation.

Most lines of evidence support that the sulphur system, microbiologically mediated, is the main redox controller in the deepest and most saline groundwaters. On the other hand, Littorina-rich brackish groundwaters show variable and very high iron contents, in agreement with what has been observed in similar groundwaters elsewhere. The microbial analyses found only trace amounts of sulphate reducing bacteria (SRB) in these samples, but very high numbers of iron-reducing bacteria (IRB). However, there is no correlation between Fe^{2+} concentration and the number of IRB in these groundwaters. Moreover, they show very low but detectable contents of dissolved S^{2-} and the $\delta^{34}S$ values are very homogeneous (around 25‰) and clearly higher than in the present Baltic Sea, indicating that sulphate reduction has occurred. These observations could support the existence of an iron-sulphide precipitation process during the Littorina Sea phase of these groundwaters, but not being intense enough to effectively limit Fe^{2+} solubility.

A modelling approach, where observed fracture mineral phases were considered, was used to simulate the current composition of the groundwater in the Forsmark area by modelling the evolution when introducing Littorina Sea water. These results indicate that re-equilibrium reaction processes are important in the control of some parameters such as pH (as well as Eh, and some minor-trace elements), moving the waters towards the adularia-albite boundary. However, the main compositional changes, and even the extent of re-equilibration processes, are controlled by the extent of the mixing process.

Uranium contents have been analysed in surface waters (Lake and Stream waters), in near-surface groundwaters from Soil Pipes and in groundwaters from the percussion and cored boreholes. The surface and near-surface waters are characterised by values between 0.05 and 28 µg/L (Figure 3-19). Large variations in uranium content in surface waters are common and are usually ascribed to various redox states (oxidation will facilitate mobilisation of uranium) and various contents of complexing agents, normally bicarbonate (which will keep the uranium mobile). Lower uranium content with depth is expected due to decreasing redox potential and decreasing HCO_3. The groundwaters sampled in the cored boreholes, in contrast, show no such depth trend. Instead, most of the groundwaters show high values (> 30 µg/L) at depths between 200 m and 600 m.

It is noted that the high but variable uranium contents are accompanied by increased ^{226}Ra and ^{222}Rn. Therefore SDM F1.2, section 9.5.9, suggests that that uranium and radium along the fracture pathways have been mobilised to various degrees by the slowly descending Littorina Sea waters. One possible scenario is that the glacial melt water is accompanied by oxidised uranium into the deformation zones and subsequently easily remobilised by the reducing but bicarbonate (and DOC) rich Littorina Sea water. The mobilised uranium was then transported to greater depths during the density turnover.

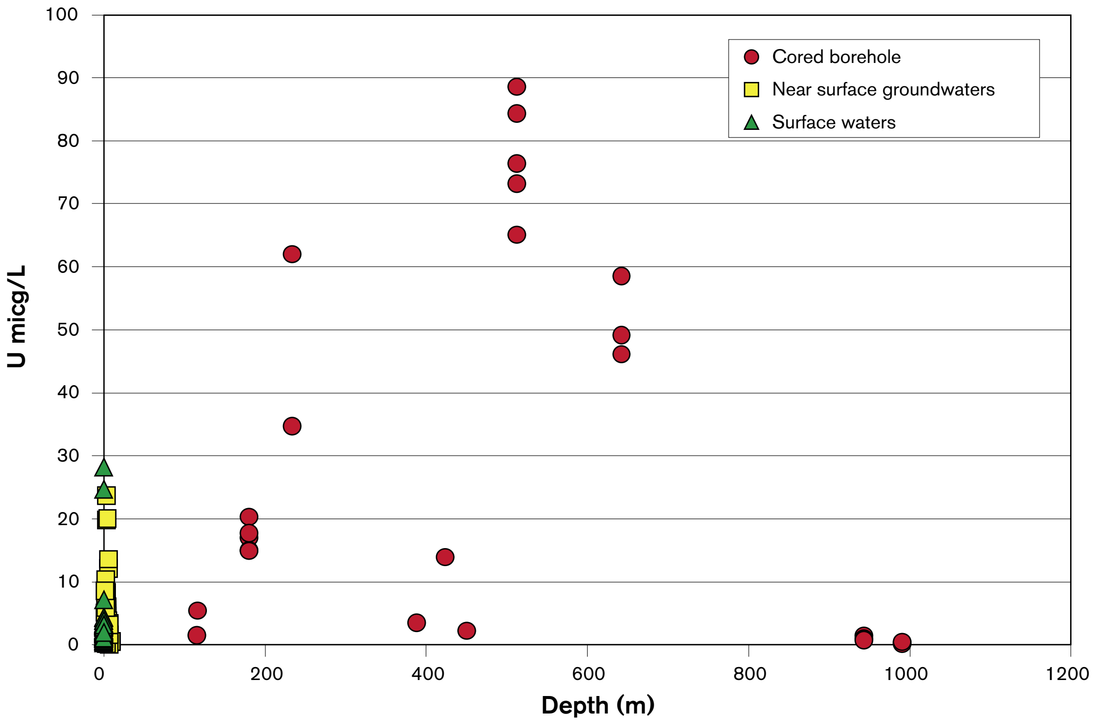

Figure 3-19. *Uranium content (µg/L) in surface and groundwaters from the Forsmark area. (Figure 9-19 in SDM F1.2).*

The hydrogeochemical modelling indicates that the groundwater samples from KFM02A: 509–516 m and KFM03A: 448–453 m, shown in Table 3-14, are representative of the groundwater composition at potential repository depths. The table also shows the limits implied by criteria and other safety considerations (see section 3.6.1).

As further discussed in Chapter 12 of SDM F1.2, the main uncertainties in the version 1.2 hydrogeochemical model are:

- Spatial variability of hydrochemistry in three dimensions at depth.
- Temporal (seasonal) variability in surface water chemistry, which ultimately impacts the identification of discharge and recharge areas.
- Model uncertainties (e.g. in equilibrium calculations, migration and mixing).
- Identification and selection of reference waters. There is a judgemental aspect of the M3 (principal components) analysis.
- Groundwater composition in the rock matrix.

Table 3-14. Analysed values of representative samples at potential repository level in the Forsmark area: i.e. KFM02A: 509–516 m and KFM03A: 448–453 m, for the chemical parameters included in requirements and preferences. (Based on Table 9-3 in SDM F1.2).

	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
KFM02A: 509–516 m	–140	7.0	9.2	2.1	< 0.1	1,160
KFM03A: 448–453 m	–250	7.5	9.2	1.2	< 0.1	1,187

There is uncertainty in spatial variability in three dimensions at depth, as the information density concerning borehole groundwater chemistry is low. Groundwater sampling causes mixing at the sampling point and the samples represent an average composition. However, a validation test has been conducted where representative/non-representative samples have been interpolated. Locally there were samples with as much as 50 percent drilling fluid, but if these unrepresentative samples were included in the site scale interpolation the impact on the result was only in the order of ± 10 percent, see Chapter 9 of SDM F1.2.

There is a strong coupling between hydrogeology and hydrogeochemistry, since it is suggested that mixing is the main process for groundwater evolution. Furthermore, density differences, created by varying salinity, affect the flow regime. These couplings are considered in the modelling work. Present-day salinity and water type distribution are "calibration targets" for simulation and the hydrogeological modelling considers the density effects. However, it is not trivial to match the hydrogeological model to the chemical data, and vice versa. For example, in the SDM F1.2 modelling it was not possible to fully match the rather high salinity in some of the boreholes. This could partly be due to a too coarse discretisation. Also the chemical data could be rather insensitive to key aspects of the hydrogeological model (i.e. the flow characteristics in the repository area), but very sensitive to other aspects – like the details of the near-surface hydrogeology or the initial conditions at the time of the last glaciation. Further enhancement of the interactions between hydrogeology and hydrogeochemistry would be warranted, but it is also important to understand the limitations to achieving full integration.

3.6.3 Safety implications

The previous sections show that the Forsmark area meets all hydrogeochemical requirements and preferences.

- Table 3-14 shows that the groundwater composition sampled at potential repository depth in the Forsmark area lie well within both the required and preferred bounds.
- Furthermore, even if the exact spatial distribution of the water composition is uncertain, essentially all water types conform to the hydrogeochemical criteria. Specifically, there is no indication of dissolved oxygen at depth and measured TDS levels range from 0 to at most 16 g/L. 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 within the range of the required and preferred criteria also in the future.

Overall, there is judged to be a rather good understanding of the hydrogeochemistry at the site. Even though the hydrogeological modelling did not fully match the rather high salinity in some of the boreholes, this is more likely dependent on details of the near-surface hydrogeology or the initial conditions at the time of the last glaciation than on the conditions at depth. Of more concern is that the current understanding of conditions at depth is based on quite scarce data. 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. For example, a more definite explanation of the high uranium content found at depth is needed. The additional data and evaluations suggested for this in SDM F1.2 continue to seem 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 of the rock and amount of fracture minerals in contact with the flowing water would be needed.

3.7 Radionuclide transport

The only pathway through 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 position 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 coming 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 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 F1.2, the site descriptive modelling of transport properties only considers retardation parameters (porosity, diffusivity and sorption coefficients), whereas the flow-related migration properties are handled outside the Site Descriptive Model report. Site investigation data from porosity measurements and diffusion experiments (*in situ* and in the laboratory) have been available for the SDM F1.2 modelling. The work has included evaluation of data from the geological and hydrogeochemical descriptions, in addition to the evaluation of transport data.

The sample collection consists of about 320 rock samples, from the major rock types, fractures and deformation zones, but it also includes altered bedrock and minor rock types. In summary, the data are analysed as follows.

- The method used for determination of porosity consists of a water saturation of the sample, followed by a drying step.
- 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.
- Laboratory resistivity and through-diffusion measurements indicate a clear correlation. A tendency to increased formation factor with increasing porosity can also be observed.
- The in situ measurements yield a considerably lower formation factor than the corresponding laboratory measurements. Furthermore, for the laboratory resistivity measurements, a tendency to increasing formation factor with increasing borehole depth is observed. No such increase is observed for the in situ results, which could be interpreted as sampling causing stress release and opening of the pores of the laboratory rock samples. Cautiously, it is thus concluded that diffusivities based on the in situ resistivity measurements are used for the Forsmark 1.2 transport properties description.
- No sorption data is reported in SDM F1.2 version; however, available BET surface area measurements indicate that materials associated with fractures and deformation zones have high sorption properties.

Table 3-15 summarises the mean values and standard deviations (expressed as mean value ± one standard deviation) of the transport parameters of the rock mass.

As further discussed in SDM F1.2 there is uncertainty in matrix retention properties, due to the spatial variability, the limited data set and the lack of site-specific sorption data. 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 that considerable systematic differences are 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 to have been exposed to stress release. Additional information and analysis is needed for a better quantification of the uncertainties and biases associated with the different methods.

Table 3-15. Suggested transport parameters (water saturation measured porosity and *in situ* electrical resistivity measured formation factor) for the common rock types at the Forsmark area. (From Table 11-2 in SDM F1.2).

Rock type (SKB code)	Log_{10}(Porosity) (vol-%)	Log_{10}(Formation factor) (–)
Granite to granodiorite, metamorphic, medium-grained (101057)	–0.68 ± 0.15	–4.68 ± 0.24
Granite to granodiorite, metamorphic, medium-grained (101057), episyenetic samples	1.05 ± 0.36	–2.23 [A)]
Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained (101051)	–0.64 ± 0.17	–4.93 ± 0.08
Pegmatite, pegmatic granite (101061)	–0.41 ± 0.22	–4.83
Amphibolite (101217)	–0.75 ± 0.28	–4.58
Granodiorite metamorphic (101056)	–0.52 ± 0.28	Pending
Felsic to intermediate volcanic rock, metamorphic (103076)	–0.11	Pending

[A)] Based on through-diffusion experimental results.

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 Forsmark.

The uncertainty is anyway quantified as a range of properties. This means that the uncertainties can be quantified, as indicated in Table 3-15.

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 Discrete Fracture Network model it is necessary to consider the actually measured information and possible distribution of flow paths in the rock in order to obtain a reasonable lower 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, for this PSE a more simplistic approach is used, exploring the possible ranges resulting from the hydraulic data, e.g. as expressed in Table 3-10 above. Furthermore, given the complexities of the 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·T·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:

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

i.e. in this case the transport resistance is independent of the width of the migration path. Assuming a gradient of 0.5 percent, which is certainly higher than found at the site at 400 m depth, and a migration distance of 100 m results in the transport resistances listed in Table 3-16.

Table 3-16. 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)	log_{10}(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

According to Table 3-10 the measured transmissivity in Volume B ranges between $2.7 \cdot 10^{-10}$ m^2/s and $2.2 \cdot 10^{-9}$ m^2/s and the transmissivity in Volume D is less than $3.9 \cdot 10^{-10}$ m^2/s. If these transmissivity values are typical, the transport resistance in Volume B would be in the order of 10^6 yr/m to 10^7 yr/m and above 10^7 yr/m in Volume D. Furthermore, in Volume B there are about 0.7 fractures per 10 m in this range, indicating that most canister positions will be intersected by such a fracture, whereas in Volume D there are about 0.02 such fractures per 10 m suggesting that most canister position will not be connected to a fracture of significant flow. Interestingly, these values are similar to the values obtained in the regional groundwater simulations by /Hartley et al. 2005/, see next subsection.

It should also be noted that the above analysis assumes that each measured PFL-anomaly is represented by a single fracture. If the transmissivity is shared between several fractures, the individual fracture transmissivity would decrease and the transport resistance increase.

Furthermore, the various DFN-analyses also point out the possibility of a few fractures having higher transmissivity, possibly in the order of 10^{-7} m^2/s or higher. This would correspond to a few migration paths with F in the order of 10^4 yr/m or lower. However, only very few canisters would be intersected by such conductive fractures. As demonstrated in section 3.2.6, less than 3 percent of the potential deposition holes could be intersected by fractures with radii larger than 50 m.

Spatially varying transmissivity – network of narrow channels

It may well be argued that the flowing features observed in the boreholes do not represent fractures with constant properties in the fracture plane, but rather intersections with channels of limited extent transverse to the flow direction. Such channels could simply be the net result of a strongly spatially varying aperture in the plane of the fracture. It has also been suggested that another possibility for such channels to develop would be along fracture intersections. An assumption of (extreme) channelling both affects the assessment of transport resistance and the probability of a deposition hole being connected to a flowing feature.

Equation (2) is interesting because it suggests that the F-factor is not influenced by channel width. However, a note by Neretnieks and Moreno, 2005 given in Appendix A, point out that the transmissivity of the channel must have been correctly evaluated from the hydraulic measurements in the boreholes. This might well be the case for $W >> D_{hole,}$ where D_{hole} is the borehole diameter. It has commonly been assumed that the channels are wide and intersect all the circumference of the borehole. However, if the channel is narrower, like a tube, the flow may have been linear and another relation should have been applied to determine the flow resistance in the channel.

According to the note by Neretnieks and Moreno, 2005 (Appendix A), it is probably better to assume that κ = "T·W", i.e. a "conductivity" of a channel with limited extent has been determined. κ has units m^3/s. Then equation (2) should be modified to

$$F_{W<Wcrit} = 2WL/(\kappa grad(H)) \text{ if } W < W_{crit} \quad (3)$$

Thus, for narrow channels $W < W_{crit}$, the F-factor decreases with channel width. For example, if $W_{crit} = 2D_{hole}$ and $W = 0.5D_{hole}$ (i.e. covers half the borehole), the corresponding F-values should be decreased by a factor of 4. However, also with these rather pessimistic assumptions the transport resistance will still generally be higher than 10^5 yr/m. It should also be noted that equation (3) underestimates the transport resistance for very narrow channels, as the diffusion into the matrix would then be radial and not plane. Assuming narrower channels than $0.5D_{hole}$ would thus be overly pessimistic.

Despite the low frequency of measurable features in the borehole, the probability of hitting these features with a wider deposition hole increases significantly if the channel width is small. It can generally be shown that the probability of a line hitting a cylinder of diameter D and height H is proportional to DH /Santaló, 1976/. For infinitely small channels the frequency of channels hitting a deposition hole, P_{20Can} is given in the note by Neretnieks and Moreno, 2005 (Appendix A):

$$P_{20Can} = (D_{Can}/D_{Hole})\cdot P_{20hole} \quad (4)$$

where D_{can} is the diameter of the deposition hole, D_{hole} the diameter of the borehole and P_{20hole} the frequency of flowing features in the borehole. This equation is based on simple geometrical reasoning and just expresses the much larger "hitting area" provided by a wide deposition hole compared with that of a thin borehole. In this simplified formulation, channels hitting the bottom or top of the deposition hole are neglected.

With D_{Can} = 1.5 m and D_{hole} = 0.076 m, this implies that $P_{20Can} = 20\cdot P_{20hole}$.Using the values of P_{10PFL} in Table 3-10 and letting them equal P_{20hole} results in P_{20Can} = 1.6 in Volume B and P_{20Can} = 0.03 in Volume D. This means that, with a deposition hole height of about 10 m, such infinitely thin channels could intersect essentially all deposition holes in Volume B and about a third of the deposition holes in Volume D.

Clearly, the above example is extreme. The channels would not be infinitely thin and the migration would not continue along a single channel. Mixing between channels and transverse diffusion into more stagnant water could possibly increase the transport resistance dramatically. Furthermore, the estimation of channel density using equation (4) is based on simple geometrical reasoning. It needs to be checked whether these densities are reasonable in relation to the observed fracturing. Nevertheless, this simple example points out the need for further exploring what would be an appropriate conceptual model for migration at the Forsmark site.

Results from regional flow simulations

As already discussed in section 3.5.3, /Hartley et al. 2005/ have calculated flow paths in the regional-scale, equivalent porous medium hydrogeological model, from release areas approximately located within the target area at 400 m depth. The groundwater model is transient and considers density dependent flow, but the flow paths are only assessed for the velocity field simulated for the present day. The particles are released within a rectangle with a spacing of 50 m, see Figure 3-16. As a separate effort, and not reported in the SDM F1.2, /Hartley et al. 2005/ 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.

In the SR-Can assessment the Darcy velocity at canister scale and the transport resistance, F, will be calculated from nested Discrete Fracture Network and Equivalent Porous medium flow simulations, where the repository region is described as a DFN at the detailed scale, as already 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}. According to /Hartley et al. 2005/ P_{32c} would equal about 1 m^{-1} in Volumes F and G. However, in Chapter 8 of SDM F1.2 it is noted that the P_{32c} value is highly uncertain and with range at least between 0.069 and 1.2 (see Table 8-11 of SDM F1.2). Although /Hartley et al. 2005/ selected a value of a_r = 1 m^{-1} for their further analyses, they also explored the sensitivity to setting a_r = 0.25 m^{-1}.

Table 3-17 provides a statistical summary of the calculated performance measures for a Base Case (HCD3_BC_HRD3EC_HSD1_BC1), with a_r set to 1 m^2/m^3 and a hydraulic conductivity of the rock mass representing Volume E, see 3.5.2, i.e. not the very much lower conductivity of Volume G (or of Volumes B and D arising from the division made by /Follin et al. 2005/).

Table 3-17. Statistical summary of the calculated performance measures (t_w, q_c, F and L) for the ensemble of particles released in the local-scale release-area for the Base Case (HCD3_BC_HRD3EC_HSD1_BC1), equivalent porous media model. Note that the rock mass was given a hydraulic conductivity representing the more permeable "Volume E", rather than the very low permeability found at the potential repository depth. (From /Hartley et al. 2005, Table B-1/).

Statistical entity	$Log_{10}(t_w)$ [y]	$Log_{10}(q_c)$ [m/y]	$Log_{10}(F)$ [y/m]	$Log_{10}(L)$ [m]
Mean	2.482	–4.142	6.160	3.040
Median	2.454	–4.098	6.071	3.000
5th percentile	1.363	–5.023	5.280	2.687
25th percentile	1.790	–4.450	5.621	2.793
75th percentile	3.043	–3.810	6.696	3.268
95th percentile	3.851	–3.381	7.259	3.519
Std dev	0.803	0.497	0.629	0.274
Variance	0.644	0.247	0.396	0.075
Skewness	0.422	–0.267	0.300	0.449
Kurtosis	–0.482	0.407	–0.930	–0.836
Min value	0.928	–6.099	4.693	2.620
Max value	4.816	–2.280	8.122	4.130

The calculations have also been performed for some of the other variants explored by /Hartley et al. 2005/. These were the following:

- *Transmissivity uncorrelated to size in the underlying hydrogeological DFN model.* The block conductivity distribution generated with the uncorrelated transmissivity is slightly higher and smoother compared to the correlated case. This causes the Darcy flux to increase and the transport resistance to decrease by about 10 percent.
- *Variant geological DFN with different power-law fracture length PDF (kr = 2.75), uncorrelated transmissivity model.* The results for the variant geological DFN with uncorrelated transmissivity only show some effect on the shape of the distribution of calculated results, but the mean and spread are essentially not affected.
- *Lower flow-wetted-surface,* $a_r = 0.25\ m^2/m^3$. Changing the flow-wetted surface per volume of rock has an impact mainly on the transport resistance, the F-values. The median and the 95th percentile of the F-value are essentially proportional to a_r.
- *Increased background conductivity outside RFM017/029.* Increased conductivity outside RFM017/029 does not have an impact on the transport results. This is expected, since most of the released particles do not go very far (median path length is about 1 km).
- *Alternative Case (AC) HCD model.* The Alternative Case HCD model gives slightly lower canister flows and longer travel times, but the F-value and the path length remain almost unchanged.

Overall, it can be concluded that due to the localized flows in the model, structural changes made to the region outside the candidate area have little effect on the flow and transport inside the volume. Generally, the sensitivity study shows that the model is not very sensitive to the changes considered and the differences compared with the Base Case are small. The variations in the performance measures between the variants considered is generally low, around 5–10 percent. The uncertainties around the value of the flow-wetted surface should be addressed further, since this has a significant impact, mainly on the transport resistance (the F-value). A more detailed discussion on these analyses is given by /Hartley et al. 2005, Appendix B/.

As already noted there are several uncertainties related to the value of a_r. One important uncertainty is the impact of the averaging resulting from the porous medium description. Another, related, uncertainty is the degree of channelling. Given the high uncertainties in the hydrogeological description, and the modelling observation of a sparsely connected fracture network the results could only be used with caution. It needs also be remembered that the analysis is based on data from the much more permeable Volume E rather than data from the volume of the potential repository. 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 needed. For this reason, the first order evaluation of the transport resistance made in this PSE is needed as a complement.

Overall remarks

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. As already noted in section 3.5.2 and in SDM F1.2, the division into volumes of different hydraulic properties as well as the estimation of hydraulic properties inside these volumes are uncertain. For example, it could be argued that the division into different volumes identified in the hydrogeological modelling is the “arbitrary” effect of a very sparsely connected network of fractures (or channels). More boreholes would be needed to determine whether the different volumes really are well defined in space. Also, borehole TV-logs might be used in estimating the width of channels.

However, the first-order analysis suggests that quite robust lower bounds on the transport resistance can be made. Generally, the analysis suggests a transport resistance above 10^6 yr/m. Only very few canister positions, if any, would be intersected by migration paths with transport resistance less than 10^4 yr/m, even assuming extreme channelling. Furthermore, depending on assumptions on the channelling (and on the division of volumes), a large percentage of the deposition holes would not be connected to any flowing features at all.

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. The previous sections show that a repository placed at 400 m depth, or deeper, in the target area of the Forsmark area meets all preferences on transport properties.

- The statistical summary in Table 3-17 shows that there are no starting positions with a calculated Darcy velocity above 0.01 m/yr. The result is little affected by the different variant cases explored. Furthermore, the analysis is based on hydraulic data for rock that is much more permeable than what is suggested valid for the rock at depth in the target volume.
- The statistical summary in Table 3-17 also shows that all calculated migration paths in the regional porous medium analysis have a transport resistance F above 10^4 yr/m and that only 5 percent of these paths have a transport resistance F less than $2 \cdot 10^5$ yr/m. The result is little affected by the different variant cases explored. Furthermore, the analysis is based on hydraulic data for rock that is much more permeable than what is suggested valid for the rock at depth in the target volume. However, the analysis and the underlying hydrogeological description are subject to many uncertainties.
- A first order analysis suggests that quite robust lower bounds on the transport resistance can be established. Generally, the analysis suggests a transport resistance above 10^6 yr/m. Only very few canister positions, if any, would be intersected by migration paths with transport resistance less than 10^4 yr/m, even assuming extreme channelling. Furthermore, depending on assumptions on the channelling (and on the division of volumes), a large percentage of the deposition holes would not be connected to any flowing features at all.
- The ranges of transport parameters for the major rock types in the Forsmark area, shown in Table 3-15, are within the ranges considered in SR 97, although the Formation Factor (which could be as low as $1.2 \cdot 10^{-5}$) 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 $4.2 \cdot 10^{-5}$. However, there are no site-specific sorption data for Forsmark.

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. As already noted in section 3.5.2 and in SDM F1.2, the division into volumes of different hydraulic properties as well as the estimation of hydraulic properties inside these volumes are highly uncertain. For example, it could be argued that the division into different volumes identified in the hydrogeological modelling rather is the “arbitrary” effect of a very sparsely connected network of fractures (or channels). More boreholes and subsequent assessment of the data would be needed to determine whether the different volumes really are well defined in space. However, as already noted the first-order analysis suggests that quite robust lower bounds on the transport resistance can be established.

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.

There is a need to reduce the uncertainty in the site description. Most uncertainties concern the hydrogeological DFN-model, and both additional data and additional evaluation analyses are warranted, see also the final discussion in section 3.5.4. In addition to this there is a need, if possible, to reduce the uncertainty in characterising the effects of channelling. However, this can only partly be achieved by new measurement approaches. Further attention to modelling, with different alternatives and careful scrutiny of assumptions, appears to be the way forward. For example, it needs to be checked whether possible channel densities are reasonable in relation to the observed fracturing, see end of section 3.7.3.

It is premature in the PSE to assess potential data needs for improving the description of the migration properties of the rock matrix – or even if such improvements will be needed. More *in situ* data would nevertheless 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 Forsmark area 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 are 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 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 Forsmark area is provided in /SKB, 2005c/. 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 Forsmark 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 even considering remaining uncertainties, the Forsmark 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 Forsmark candidate area does not have any ore potential. 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 target area, i.e. a part of the candidate area, while meeting the required respect distances to the deformation zones even if assuming a low degree of utilisation of potential deposition holes.
- Only a few percent of all potential deposition holes would be intersected by discriminating fractures of radius larger than 50 m, but the number is uncertain due to the uncertainty in the DFN-model of the fractures.
- A repository can be constructed, at least down to –500 m, without expecting problems with extensive spalling or rock fallout. The risk for spalling in the deposition tunnels oriented perpendicular to the maximum horizontal stress increases significantly below a repository depth of 450 m. This risk is eliminated at all repository depths if the deposition tunnels are oriented parallel to the maximum horizontal stress. At less than 400 m depth the probability for spalling in the vertical deposition holes is judged to be very small, and still at a depth of 650 m the probability of spalling is less than 1 percent. Hence these results suggest that spalling will not be encountered along the deposition holes, regardless of the repository depth, but there are uncertainties in the analyses and in confidence in stress below 500 m is lower.
- It is possible to define a layout that ensures that the required temperature conditions on canister and buffer are fulfilled.
- The groundwater composition sampled at potential repository depth in the Forsmark area lies well within both the required and preferred bounds. Furthermore, even if the exact spatial distribution of the water composition is uncertain, all the four water types identified also fulfil the hydrogeochemical criteria. This also means that it is likely that the groundwater composition will remain within the range of the criteria also in the future.

The evaluation also shows that the Forsmark candidate area *meets all of the safety preferences*, but for some aspects of the site description further reduction of the uncertainties would enhance the safety case. However, all such enhancements need not necessarily be achieved during the Site Investigation phase. More detailed conclusions are given below:

- The stress levels are comparatively high. For the depth of 500 m, an average maximum horizontal stress of about 45 MPa is estimated and this estimate is also uncertain. This implies attention to construction and stability problems, especially if the repository were to be located at greater depths than 500 m.
- There are uncertainties in the description of the hydraulics of the rock mass due to the sparseness of conducting fractures or channels. However, according to the models there are essentially no blocks at the 20 m scale with hydraulic conductivity K above 10^{-8} m/s in the volumes where the repository is located in the currently suggested layout. Nevertheless, 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.
- The evaluation of flow-related transport parameters conducted with the regional groundwater flow model shows that both the preferences for Darcy velocity and the preference for transport resistance F are met for almost all potential migration paths. The analysis has not been made with sufficient resolution for this conclusion to be definitive, and there are also substantial uncertainties with respect to the channelling of individual fractures. However, a first-order analysis suggests that quite robust lower bounds of the transport resistance can be made, but further reduction of the uncertainties in the transport description is needed. In particular, different assumptions on channelling affect both the transport resistance and the probability for an individual canister to be connected to the flowing features.
- The migration properties of the rock matrix (porosity and formation factor) meet the preferred values. However, the values on which this conclusion are based come from a few samples only.

Consequently, from a safety point of view, there is no reason not to continue the Site Investigations at the Forsmark site. There are still uncertainties to resolve and the safety would eventually need to be verified through a proper safety assessment. Still, this Preliminary Safety Evaluation demonstrates that it is likely that a safe repository for spent nuclear fuel of the KBS-3 type could be constructed at the site.

4.2 Feedback to the continued site characterisation

The Site Descriptive Model, i.e. SDM F1.2, is based on the Initial Site Investigation of the Forsmark area, and the model report /SKB, 2005a/, states that there is uncertainty associated with the description. However, the main uncertainties are identified and in some cases quantified, or explored as alternatives. This Preliminary Safety Evaluation shows that only some of these quantitative or qualitative 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 inside the target area would be needed to firmly ensure the suitable deposition volumes. The additional data as suggested in SDM F1.2 and subsequent evaluation appear appropriate for this purpose.

- There is substantial uncertainty in the DFN-model. Efforts need to be spent on reducing these uncertainties. During the Site Investigation Phase, this can partly be achieved with more data, as further discussed in Chapters 12 and 13 of SDM F1.2, but there is a limit on the extent to which these uncertainties could be reduced using only surface based information. 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 that 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 works 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 better use of the borehole information. It is particularly important to provide robust estimates of the intensity of large fractures and features, e.g. the k_r parameter in the power-law distribution and further efforts should be spent on providing good support for the possible range of this parameter. In contrast, details of the orientation distribution of fractures are of much less importance.
- Considering the high and uncertain stress levels further reductions of the uncertainties in stress and rock mechanics properties are needed. The additional data suggested in Chapter 13 of SDM F1.2 appear appropriate to fill these needs. Also, the issue of spalling due to the thermal load may 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. Issues worth considering include assessing the potential anisotropy of the thermal data and the size distribution of the subordinate rock types within RFM029. The planned data and modelling envisaged in Chapter 12 and 13 of SDM F1.2 appear justified.
- Even though the current model indicates very low hydraulic conductivities at potential repository depth, additional site data are needed in order to confirm the extent of the low permeability volumes. The uncertainties in the spatial variation and upscaling of the hydraulic properties warrant further studies. Furthermore, reducing the uncertainty in hydraulics of the fracture network would allow for much less pessimistic handling of the transport resistance in the rock mass. Suggestions for how to reduce the uncertainties are given in Chapters 12 and 13 of SDM F1.2.
- Even if the hydrogeochemical requirements and preferences are met, further reduction of uncertainties would improve the understanding of the hydrogeochemistry and would enhance the safety case. For example, a more definite explanation of the high uranium content found at depth is needed. The additional data and evaluations suggested for this in SDM F1.2 are considered justified.
- In order to have a full evaluation of the redox buffering capacity of the geosphere, more mineralogical data, Fe(II) and sulphide content of the rock and amount of fracture minerals in contact with the flowing water would be needed.
- There is a need, if possible, to reduce the uncertainty in characterising the effects of channelling. Possibly, borehole TV-logs might be used in estimating the width of channels. However, reducing uncertainty can only partly be achieved by new measurement approaches. Further attention to modelling, with different alternatives and careful scrutiny of assumptions, appears to be the way forward. For example, it needs to be checked whether possible channel densities are reasonable in relation to the observed fracturing.

- It is premature in this PSE to assess potential data needs for improving the description of the migration properties of the rock matrix – or even if such improvements will be needed. More in situ data would nevertheless enhance the safety case. Better feedback on this issue will be available in relation to the full migration analysis made within the SR-Can assessment.

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 the deposition holes intersected by discriminating fractures or deformation zones. This assessment would also produce more realistic estimates of the degree-of-utilisation.

It seems important, as is acknowledged in the currently suggested design, to orient the deposition tunnels parallel to the direction of the maximum horizontal stress, in order to avoid extensive spalling problems in those tunnels.

The designed 6 m spacing of canister deposition holes appears to be sufficient. Considering the current estimate of spatial variability of thermal conductivity suggests that essentially all canister positions would result in a maximum temperature at the canister surface below 100°C. In the analysis the highest canister surface peak temperature recorded was 100°C and this would only occur for very few positions. At least locally, it may be possible to use smaller canister spacing, or to reduce the spacing between the deposition tunnels, but this would require a more detailed understanding of the spatial variability of the thermal properties.

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 would need special or additional attention in any full long-term safety assessment of a deep repository for spent nuclear fuel at the Forsmark site. 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 radius larger than 50 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 high rock stresses spalling during construction and operation appear 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.

Much of the rock mass at potential repository depth appears to have very low permeability. While this is an advantage with regard to retention of potentially released radionuclides, the very low permeability may also imply long saturation times for the buffer. Long saturation times are not necessarily a disadvantage, but the issue needs nevertheless to be looked into in SR-Can.

The first-order analyses of transport resistance demonstrate the importance of channelling, but also that there is a potential limit to the variability in this important parameter. SR-Can will need to further assess these uncertainties and possibilities for bounding the transport resistance estimates.

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. The site-specific information on the migration properties of the rock needs 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 volume. 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 Forsmark area. Examples of such issues are the potential impact of nearby nuclear power plants and the power cable to Finland and the effect of a deep mine excavation near but outside of the tectonic lens.

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A note on flow and transport in sparse networks- Implications for the Forsmark site

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■ Summary

Observations suggest that fluid flow takes place in complex three dimensional networks of channels in the fractures and in the fracture intersections in fractured crystalline rock. The channels can be narrow, from mm:s to some tens of cm. Boreholes are used in site investigations to find the water conducting channels. Their frequency and transmissivity distribution is assessed by packer and other water injection/withdrawal tests. This information can be used to estimate the probability for channels to intersect deposition holes for canisters containing nuclear waste. The Flow Wetted Surface of such networks is explored as well as the F-factor (A measure of the capacity of the rock to retard solutes). It is found that very few channels will be intersected by even a long borehole in a not very sparse network. If only one conductive channels is found every 200 m at repository depth the probability of such channels intersecting a canister is quite high.

This note was put to paper under strong time constraints and is not to be seen as more than a quick attempt to shed some light on channeling effects.

This note is written in Mathematica and transformed to a PDF file. Not all information is shown in the PDF file.

■ Introduction

It has been found in Forsmark that at repository depth very few conductive channels have been intercepted by the boreholes. Typical average spacing is on the order of hundred(s) of meters. The borehole diameter used was 0.076 m. We want to explore how sparse the network is and what FWS is available in the network. We also want to assess the F-factor (FWS/flowrate). Further we wish to study how the size of the conductive channels would influence the F-factor and the probability of channels intersecting a canister.

To begin with, to illustrate the idea we determine the density of infinitely thin randomly oriented channels expressed as $P_{20,}$ which means the number of (infinitely) thin and long channels that intersect a surface in the 3 dimensional space (Number of channels /m^2). This is directly found from the number of intersections of flowing channels found in a borehole of length Lhole and diameter Dhole.

$$P_{20} = \frac{\text{Nchannels}}{\text{Lhole Dhole}} = \frac{1}{H\,\text{Dhole}} \qquad (1)$$

H is the mean distance between channels intercepting the borehole

This can directly be used to estimate the frequency of channels that will intersect the deposition holes. Neglecting end effects the IntersectionfrequencyP20 m^{-1} is

$$\text{IntersectionFrequencyP20} = P_{20}\text{*Dcanister} \qquad (2)$$

The probability of hitting the end of the deposition hole has been neglected here. It will be shown below that when channel widths W are not negligible this can noticeably decrease the probability of a canister being intersected by a channel.

Next we estimate the average channel length per rock volume P31. This can be used for a first approximation of the specific flow wetted surface a_r when the channel width W is known.

Next a more accurate estimate of intersection probability of a borehole with randomly oriented channels of finite lengths and widths is presented and the intersection probability as well as the specific FWS a_r is presented.

The F-factor (A measure of the capacity of the rock to retard solutes) for the network is derived for the channels and it is shown that it is independent of the channel width for wide channels but decreases with decreasing W for channels smaller than a few borehole diameters.

For illustrative purposes the channels are arranged in a cubic grid to visualize how sparse/dense the grid is and for use in the Channel Network Model Chan3D (Gylling et al. 1999)

A short summary of field observations of channeling in fractured crystalline rock is presented together with some references of the observations. Channel widths are observed to range from very thin tubelike channels to widths of some tens of cm.

■ Estimate P31 from P20, FWS and Intersection probability with a deposition hole

By P31 we mean the length of channels per volume of rock. Determine the relation between P31 and P20. Again we start with the case where infinitely long and thin channels exist. The problem is approached in the following way. A surface is intersected by a number of channels with a random angle α between 0 and π. At a distance δ from the surface there is another surface parallel to the first. The frequency of channels with angle α intersecting the plane is proportional to Sin(α). The length of the channel between the two planes is $\frac{\delta}{\text{Sin}(\alpha)}$. The average length per angle increment dα thus is constant and equal to δ. The frequency of intersection for an angle increment is Sin(α)dα

Then the mean length l_{mean} of he channels between the two planes is

$$l_{\text{mean}} = \frac{\int_0^{\pi/2} \frac{\delta}{\text{Sin}(\alpha)} \text{Sin}(\alpha)\, d\alpha}{\int_0^{\pi/2} \text{Sin}(\alpha)\, d\alpha} \; \frac{\int_0^{\pi/2} \delta\, d\alpha}{\int_0^{\pi/2} \text{Sin}(\alpha)\, d\alpha} = \frac{\pi\delta}{2} = 1.5708\, \delta \qquad (3)$$

Then for an intersection density P20 there will be a channel length per volume of rock equal to

$$\text{P31} = \text{P20} * \frac{\pi}{2} \qquad (4)$$

and

$$a_r = 2\text{W P31} = \pi\text{WP20} = \pi \frac{W}{H\, \text{Dhole}} \qquad (5)$$

Moreno et al (1997) used a similar approch but assumed channels of fine length and width.

Compare this with the results obtained by Gylling et al. (1999) where also the presence of channels with a finite width and length was accounted for when assessing a_r from borehole data. In that paper spherical three dimensional random orientation was assumed so some difference is expected: Gylling et al (1999) obtained

$$a_r = \frac{2\,\text{LW}}{H(\frac{\text{LW}}{2} + \frac{\pi}{4}\, \text{Dhole}(W+L))} \qquad (6)$$

For W <<Dhole<<L

$$a_r = \frac{8\, W}{\pi\, H\, \text{Dhole}} = 2.55 \frac{W}{H\, \text{Dhole}} \qquad (7)$$

This is slightly less than the previous simple essentially 2 dimensional result.

The equivalent channel length for a cubic grid is obtained from

$$a_r = = \frac{6\,W}{Z^2} \qquad (8)$$

and

$$Z = \sqrt{\frac{6\,W}{a_r}} \qquad (9)$$

The intersection frequency for this case when W>0 is

$$\text{IntersectionFrequencyW} = \frac{ar\,(\frac{W}{2} + \frac{\pi}{4}\, \text{Dcan})}{2\,W} \qquad (10)$$

If frequencies of orientations of the fractures containing the channels and fracture intersection orientations are not evenly distributed the analysis sketched above could be extended to account for this.

■ Impact on flow and transport of solutes

The flowrate of water in fractured rocks will increase with the increasing transmissivity of the channels as well as with the number of channels. The flowrate of solutes will also increase in the same way. However, for a given flowrate of water solutes that can diffuse into the porous rock matrix will more readily do so the larger the surface is over which this can take place. Thus the wider the channels of a given length and number are the more the solutes will be retarded by the uptake and dilution in the matrix porosity. When the channels in the rock have different transmissivities (and other properties), which they naturally do, preferential flowpaths may develop.

Channeling and the importance of the Flow Wetted Surface, FWS, has been discussed in several papers and we mention just a few where we have been involved. Moreno et al. (1989) discussed channeling in fracture zones. Moreno and Neretnieks (1993 a,b) discussed channels networks and the importance of the FWS. In all such studies it is found that one parameter group the FWS/flowrate has a dominating inpact on the solute transport.

■ The F-factor

The flowrate in a channel and the F-factor are obtained from

Qflow=Trans*W*grad (11)

F-factor $= \frac{2\,W*X}{Qflow} = \frac{2*X}{Trans*grad}$ (12)

where X is the travel distance, Trans is the channel transmissivity and grad is the hydraulic gradient. Equation (9) is interesting because it suggests that the F-factor is not influenced by channel width.

However, we wish to point out that the transmissivity of the channel must have been correctly evaluated from the hydraulic measurements in the boreholes. This could possibly be the case for W>>Dhole. It has commonly been assumed that the channels are wide and intersect all the circumference of the borehole. However, if the channel is narrower, like tube, the flow may have been linear and another relation should have been applied to determine the flow resistance in the channel. It is probably better to assume that TW=Trans*W, "conductivity" of a channel with limited extent has been determined. TW has units m^3/s. Then Equation (12) should be modified to

FfactorWlessDhole= $= \frac{2\,W*X}{TW*grad}$ (13)

It should in addition be noted that in the commonly used procedures for evaluation Trans, radially symmetric flow pattern has been assumed. The values are thus probably not correct if the channels have a small width.

Thus, for narrow channels W<Dhole, the F-factor decreases with channel width. As there are several observations that fracture intersections form narrow channels with considerable flowrates this effect should not be neglected.

■ Examples

Some sample calculations are presented below. They are based on reasonably representative values. The following data are used in the example. The factor $3.15 * 10^7$ is used to transform to time in years from time in seconds.

```
In[51]:= H = 200;
         Dhole = 0.076;
         Trans = 10^-7 * 3.15 * 10^7;
         X = 100;
         grad = 0.001;
         Dcan = 1.5;
         Lcan = 10;
         P20
         W = 0.2;
         ZGylling
         ZP20
         arGylling
         arP20
         IntersectionFrequencyP20
         IntersectionFrequencyW

Out[58]= 0.0657895

Out[60]= 9.78847

Out[61]= 5.38794

Out[62]= 0.0125242

Out[63]= 0.0413367

Out[64]= 0.0986842

Out[65]= 0.040018
```

■ Interception frequency of a canister

The interception frequency is a measure of how frequently a deposition hole is intercepted by a channel. The inverse of the intersection frequency can be seen as the mean distance for a canister hole is intersected by a channel.

```
In[66]:= Plot[IntersectionFrequencyW, {W, 0.001, 0.3}, AxesLabel → {"W m", "Frequency 1/m"}]
```

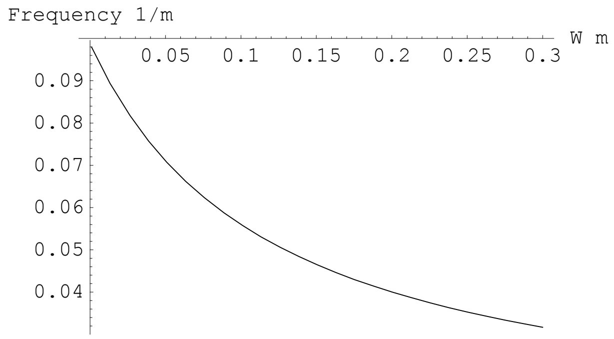

Figure 1. Interception frequency of a deposition hole as a function of channel width.

```
In[67]:= Plot[1 / IntersectionFrequencyW,
          {W, 0.001, 0.3}, AxesLabel → {"W m", "Mean distance m"}]
```

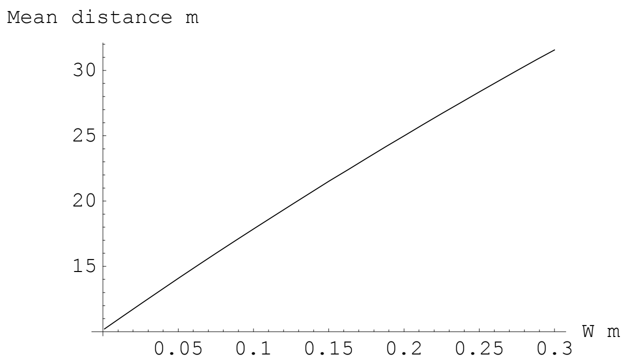

Figure 2. Mean distance between channels intercepting a deposition hole as a function of channel width.

Figures 1 and 2 show the intersection frequency and mean intersection distance of a deposition hole with 1.5 m diameter. Considering that the hole is 10 m long it is not unlikely that a hole will be intersected.

■ Size of the cubic grid

Arranging the channels in a cubic grid gives the cube sides Z shown in the Figure 3 .

```
In[68]:= Plot[ZGylling, {W, 0.001, 0.3}, AxesLabel → {"W m", "Channel Length Z m"}]
```

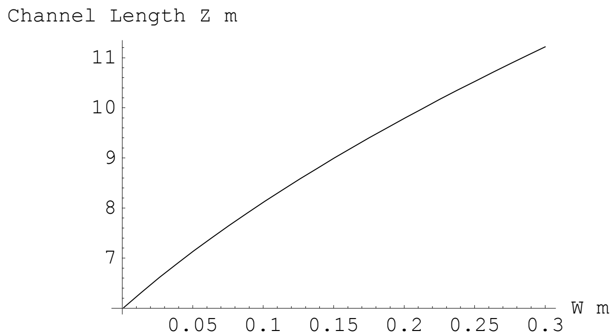

Figure 3. *Channel length if the channels are arranged in a cubic grid with sides Z as a function of channel width*

■ Flow Wetted surface a_r of rock mass

The specific FWS of the rock is shown in Figure 4.

```
In[69]:= Plot[arGylling, {W, 0.001, 0.3}, AxesLabel → {"W m", "FWS ar m-1"}]
```

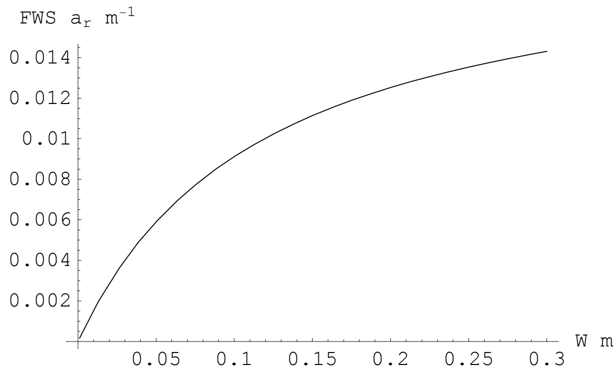

Figure 4. *The specific FWS a_r of the rock mass m^2/m^3 as a function of channel width*

■ F-factor in channels

The F-factor for channels wider than a few borehole diameters is constant but decreases with decreasing width for smaller channels. Here the boundary is taken to be at two borehole diameters.

```
In[70]:= Plot[Ffactor, {W, 0.001, 3*Dhole}, AxesLabel → {"W m", "F-factor years/m"}]
```

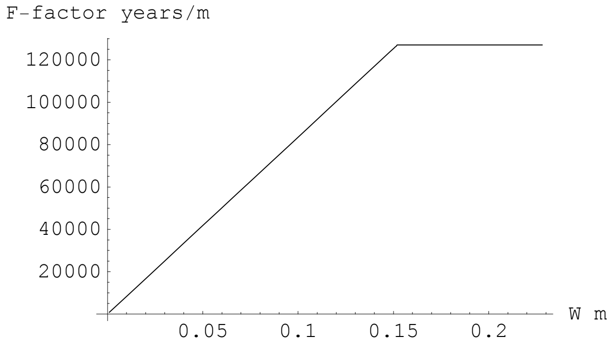

Figure 5. F-factor (FWS/flowrate) for 100 m long channels subject to a hydraulic gradient of 0.001 as a function of channel width

■ Some observations on channeling in fractures

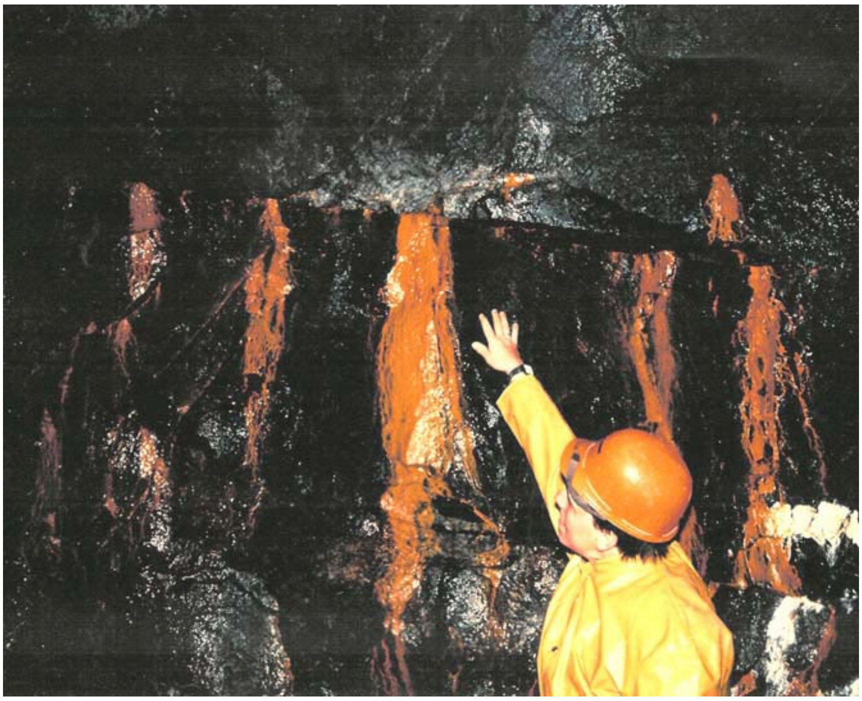

Figure 6 Channels in fractures seen as a result of iron- oxy- hydroxide precipitation

Figure 6 above shows a typical example of channels in fractures in fractured granitic rock. It is taken, together with scores more, in the Bolmen tunnel in south west Sweden. The reddish "curtains" show where water exits the fracture. The "curtains" are precipitates of iron- oxy-hydroxides and the microbes that catalyzed the oxidation of ferrous iron in the emerging water. We walked several km in the tunnel. Sometimes there were no "curtains" for many tens of meters, then one or a few isolated spots were present, often at fracture intersections. Again, tens to perhaps a hundred meter further along one or two fractures with channels like in the picture above were seen. Nowhere did we see a fracture with even flow along it.

Similar observations were made in another tunnel at Kymmen where also estimates of flowrates from the different channels were made in the "good" rock as well as in the fracture zones (Moreno and Neretnieks 1989). Similar observations were made at the site for the Swedish Low and Intermediate Waste repository at Forsmark (Moreno and Neretnieks 1993a,b). In this paper also an early attempt to analyze borehole transmissivity data to obtain the FWS was made and a 3-dimensional channel network model was used to analyze the 3D experiment results for flow as well as for solute transport. Neretnieks (1988) discussed some channeling observations in relation to flow and solute tranport.

In an experiment in Stripa a few "prominent" fractures intersecting a drift were supplied with special packers inserted a short distance into the fracture and water was collected (Abelin et al. 1983). The water flowrate to the packers varied considerably, again suggesting channeling in the fracture plane. Tracers injected at 5 and 10 m distance into these fractures were collected in the packers. Some of the tracers were sorbing and were not expected to arrive into the drift during the about year long experiment. The fracture plane was therefore excavated after the experiment and monitored for the sorbing tracers. It was found that the "prominent" fractures chosen for the experiment were intersected by other fractures near the injection location and that tracers had to a large extent migrated into these. A three dimensional network of channels was thus present.

In the Stripa 3D experiment (Abelin et al. 1991a,b) a 100 m long drift was covered with 375, 2 m^2 large plastic sheets. The drift is located 360 m below the ground surface in water saturated rock. The inflow into each sheet was monitored. A clear correlation between the number of fracture intersections and flowrates into the sheets was found. The nine different tracers injected and collected over more than a year showed that there was a complex three dimensional network of channels, indicated also by the pattern of tracer emergence into the sheets. Furthermore, tritium was found in the water in some locations indicating that the water travel time to some of the sheets must have been less than about 30 years, much less than the estimated average water travel time. This suggests the presence of some fast channels that do not mix much with other water in the system. The flow was very unevenly distributed. 1 sheet of the 375 carried 10 % of all water, 12 sheets carried 50 % and 2/3 of the sheets carried no measurable flowrate of water.

In the Channeling experiments in individual fractures a specially designed "Multipede" 2 m long packer was inserted in 20 cm diameter holes in the plane of fractures. Every "foot" of the Multipede with 20 hollow "feet" on each side were used to inject water over an isolated 50*50 mm^2 part of the hole straddling the fracture. All 40 "feet" were pressurized simultaneously as was the rest of the hole to avoid any flow from one foot to another. After one pressurization the "Multipede" was moved 50 mm and the procedure was repeated. In this way the local injection flowrates could be resolved to 5 cm sections. The flowrate between different 5 cm sections varied considerably. "Channel widths" of 5- 30 cm were found (Abelin et al 1990, Abelin et al. 1994).

Tracers were injected in one such hole and collected in another hole 2 m away in the same fracture. The experimental fracture was sealed at the face of the drift. Visual inspection of the face of the drift where the fracture with the holes was located had led us to believe that the experimental fracture was the "largest" and that the other smaller fractures should not interfere with experiment. However it was found that the tracers could not be recovered quantitatively in the collections hole. The tracers emerged in various spots in the minor fractures intersecting the face of the drift. This again was a confirmation of the presence of a complex three dimensional network of channels.

Another experiment similar to the 3D experiment was made in a small fracture zone at Stripa using plastic sheets for water and tracer collection (Birgersson et al. 1993). A similar pattern was found in the zone as in the 3D experiment, a few sheets carrying a very large fraction of the flowrate. The recovery results also suggested the presence of a small FWS in some paths.

■ Discussion and conclusions

Observations of flow in fractured crystalline rock show that water flows very unevenly in fractures and that fracture intersections often also conduct water. We call both conduits "channels" in this note. The channels typically are between a mm and up to 0.3 m wide. The channels are connected in a complex three dimensional grid. The channel density can vary considerably and e.g. very few channels have been intersected at repository depth by the deep bore-holes at Forsmark. The observations suggest that the presence of channels should be accounted for in flow and solute transport models.

Narrow channels will have less FWS than wide channels but the F-factor of the channels and of the rock mass will not be much influenced by this, provided the transmissivity distribution of the channels is the same. This applies to chan-nels wider than several borehole diameters used to locate them and to determine their transmissivity. The transmissivity of channels narrower than several borehole diameters have probably not been assigned a correct transmissivity.

The decrease of F-factor for the narrow channels is partly compensated by the changing diffusion geometry. For wide channels the diffusion is essentially perpendicular to the fracture surface and is thus one-dimensional. When the channels become narrow diffusion will increasingly become radial. This compensates to some extent for the loss of FWS.

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