



Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

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Technical Note

2012:41

Hydrogeological conditions at
the Forsmark site

SSM perspektiv

Bakgrund

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

Projektets syfte

Syftet med projektet är att ta fram synpunkter på SKB:s säkerhetsanalys SR-Site för den långsiktiga strålsäkerheten hos det planerade slutförvaret i Forsmark. Synpunkterna ska baseras på en granskning av huvudrapporten för SR-Site. I granskningsuppdraget ingår att:

- belysa den övergripande kvaliteten på SKB:s redovisning,
- identifiera behov av kompletterande information från SKB och
- ta fram förslag på kritiska frågor som behöver granskas mer i detalj i nästa fas av SSM:s tillståndsprövning.

Slutrapporten från konsultprojektet (denna Technical Note) är ett av flera externa underlag som SSM kommer att beakta i sin egen granskning av SKB:s säkerhetsredovisningar, tillsammans med andra konsultrapporter, remissvar från en nationell remiss och en internationell expertgranskning av OECD:s kärnenergibyrå (NEA).

Författarens sammanfattning

Den hydrogeologiska platsbeskrivningen och de i SR-site tillämpade grundvattenmodellerna återspeglar på många sätt framsteg i den tillgängliga tekniken för modellering av grundvattenflöde genom sprickor i kristallint berg. Avancerade metoder tillämpas för att representera naturliga vattenförande sprickor från kilometerskalan ner till meterskalan och för att representera berguttag som återfyllda tunnlar och deponeringshål.

De använda modellerna inbegriper de viktigaste fysikaliska processerna som inverkar på grundvattenflödet. Processerna är strandlinjeförskjutning, densitetsberoende flöde, blandning av vatten med olika salthalt och temperatureffekter. De senare inbegriper även permafrosttillväxt under framtida kallare klimat. Olika modellvarianter och stokastiska simuleringar används för att utvärdera de viktigaste osäkerheterna som kan identifieras med i dagsläget befintlig information.

Den hydrogeologiska analysen omfattar således många av de frågeställningar som är av vikt för säkerhetsanalysen genom påverkan på säkerhetsfunktionerna som har identifierats för SR-Site. Det finns dock fortfarande några luckor som bör fyllas åtminstone som ett led i huvudgranskningsfasen.

För det första ges systemet av vattenförande sprickor konstanta egenskaper i alla analyser (bortsett från permafrosteffekter) över hela säkerhetsanalysens tidsrymd vilken sträcker sig över en miljon år. Under framtida nedsningsar

kan man förvänta sig att horisontella sprickor i de ytligaste 150 m av berget delvis pressas samman av vikten av det två kilometer tjocka istäcket. Dessa sprickor har i dagsläget hög vattengenomsläpplighet. Sprickornas höga vattengenomsläpplighet beskrivs som en huvudegenskap som leder till minskad strömning genom det djupt liggande slutförvaret. Därför är avsaknandet av analysen av förändringar i dessa sprickor en betydande lucka.

För det andra antas i alla analyser att sprickorna är slumpmässigt fördelade i berget utan någon statistisk tendens i den rumsliga fördelningen. Konsekvenserna av alternativa modeller för den rumsliga anordningen av sprickorna bör testas. En tidigare studie på uppdrag av SSM visade att åtminstone en av de undersökta modellerna, som inte kan uteslutas baserat på befintliga data, ger flödesökningar på en storleksordning i de mest utsatta deponeeringspositionerna.

För det tredje är alla analyser baserade på tolkningen att hydrauliska konduktiviteterna i alla större deformationszoner har samma tendens att minska med djupet. En genomgång av data pekar på att denna tolkning är tveksam för åtminstone flera av de brant stupande deformationszonsgруппerna. Konsekvenserna av andra tolkningar, t.ex. möjligheten att brant stupande zoner inte blir mindre konduktiva med djupet, bör undersökas.

För det fjärde har inte alla konstruktionsförutsättningar för slutförvaret fullt ut beskrivits eller demonstrerats. I synnerhet kvarstår det att påvisa att det finns fungerande metoder för att kunna detektera och undvika stora sprickor och mindre deformationszoner. Metoderna för att säkerställa att inflödena till depositionstunnlarna efter pluggningen förblir inom tillåtna ramar har inte beskrivits fullständigt. Hur känslig den övergripande säkerheten är för att dessa kriterier kan uppnås bör kontrolleras för att avgöra ifall fullständigare planer för demonstration bör krävas innan ansökan kan tillstyrkas.

Projektinformation

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SSM perspective

Background

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

Objectives of the project

The objective of the project is to provide review comments on SKB's post-closure safety report, SR-Site, for the proposed repository at Forsmark. The review comments shall be based on a review of the main report for SR-Site. The review assignment comprises the following tasks:

- to evaluate the overall quality of SKB's reporting
- to identify need for complementary information from SKB, and
- to propose critical issues that need to be addressed in more detail in the next phase of SSM's licensing review.

The final report from this consultant project (this Technical Note) is one of several documents with external review comments that SSM will consider in its own review of SKB's safety reports, together with other consultant reports, review comments from a national consultation, and an international peer review organized by OECD's Nuclear Energy Agency (NEA).

Summary by the author

The hydrogeological site description and groundwater models employed in support of SR-Site, in many ways, represent advances in the state of the art for crystalline bedrock where groundwater moves mainly through fractures. Advanced methods are used for representing water-conducting natural features on scales from kilometres down to a meter, as well as excavated portions of the repository including backfilled tunnels and deposition holes.

The models used include representations of key physical processes that could affect groundwater flow, including changes in shoreline location, density-dependent flow, mixing of waters of different salinity, and temperature effects including formation of permafrost during future colder climates. Model variants and stochastic simulations are used to explore most of the key uncertainties that can be identified at this stage.

The hydrogeological analysis thus covers many of the issues that are of concern for safety assessment, in terms of affecting the safety functions that have been identified for SR-Site. However, there are still some gaps that should be resolved as part of the main review phase.

First, all analyses treat the system of water-conducting fractures in the bedrock as having essentially constant properties (other than the effects of

permafrost), throughout the million-year period of the safety assessment. During future glaciations, it should be expected that the weight of up to a 2 km thickness of ice will cause partial closure of horizontal fractures in the uppermost 150 m of bedrock, which are currently highly transmissive for water. The high transmissivity of these fractures is described as a key site property that helps to reduce groundwater flow through the final repository, so the lack of an analysis of the consequences of changes in these fractures is a major gap.

Second, the analyses are all based on an assumption that fractures are randomly distributed in the bedrock, with no statistical tendency for spatial organization. Consequences of alternative models for spatial organization of fractures should be tested. Previous work on behalf of SSM has demonstrated that at least one alternative model, which cannot be excluded based on the available data, yields order-of-magnitude increases in flows for the most affected deposition hole positions.

Third, all analyses are based on an interpretation that hydraulic conductivities in all major deformation zones have the same tendency to decrease with depth. Examination of the data indicates that this interpretation is doubtful for at least several families of deformation zones which are steeply inclined. The consequences of viable alternative interpretations, for instance the possibility that steeply dipping zones do not become less conductive with depth, should be checked.

Fourth, methods for achieving the design premises for the repository have not all been fully described or demonstrated. In particular, methods for avoiding large fractures and minor deformation zones remain to be demonstrated. Methods for ensuring that inflows to deposition tunnels remain within allowable limits, after placement of tunnel plugs, have not been fully described. The sensitivity of overall safety to attainment of these criteria should be checked, to determine if more fully demonstrated plans should be required prior to license approval.

Project information

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1. Main review findings

1.1. Completeness of the safety assessment

The SR-Site main report and supporting hydrogeological reports present a thorough and detailed analysis of the consequences of the hydrogeological interpretation that was developed in during site investigations (SDM-Site). Advanced modelling methods have been applied to address key issues including, for example:

- upscaling of detailed fracture-network models to site and regional scales,
- role of time-varying boundary conditions due to surface-climate evolution including future glaciations,
- mixing and density-dependent flow of waters of varying salinities,
- effects of permafrost development on flow of groundwater,
- influence of repository excavations and engineered barriers on groundwater flow,
- effectiveness of hydrogeological and geological criteria for accepting or rejecting deposition hole positions.

Results from these models (fluxes/flowrates, residence times and travel distances for water discharging from a given deposition hole to the biosphere, discharge locations at the geosphere-biosphere interface, and transport resistances) are propagated to other parts of the safety assessment in generally appropriate ways.

The main gaps in terms of hydrogeology are:

- possibilities for changes in hydraulic properties of the bedrock due to glacial loading;
- testing consequences of alternative models for spatial organization of fractures (rather than just variations in parametric correlations);
- testing alternative parametrizations for the hydraulic properties of major deformation zones (including the possibility that steeply dipping zones do not become less hydraulically conductive with depth);
- practical demonstration of methods for verifying that design premises are attained, in particularly the methods for avoiding large fractures and minor deformation zones.

These gaps are discussed in further detail in the following subsections.

In addition, the hydrogeological models do not include a conceptual model for the spatial distribution and extent of the vuggy granite which is observed to have very high permeability in cores. The extent and potential hydrogeological significance of this altered rock type should be discussed. If there are good grounds for ignoring it in the hydrogeological model, these should be explained.

Finally, R-09-22 (p. 106) notes that out-freezing of salt (salt rejection) during permafrost growth is not accounted for in the modelling of future climates. Scoping calculations of this effect were not found in this review, so this might be a gap in terms of treating processes that could possibly affect, for example, safety functions relating to near-field chemistry.

1.1.1. Constant hydrologic properties of fractures and deformation zones

The development presented in SR-Site and supporting reports does not take into consideration possibilities for changes in hydraulic properties of the bedrock due to glacial loading. This is especially significant for the “shallow bedrock aquifer” features which are likely to see the greatest changes in vertical stress during future glacial loadings. According to the SR-Site main report (p. 292 & 330) it does not appear that any changes in the properties of this feature are considered.

Similarly, rock porosity and effective diffusivity under temperate conditions are considered to be valid for all conditions in the host rock during repository evolution (TR-11-01, p. 666-667); “Even with glaciation, unlimited pore connectivity is expected.” (p. 667). Justification for this statement seems to be lacking.

According to R-09-22 p. 42, in the models of Vidstrand et al. (R-09-21) equivalent continuum porous-medium properties are taken directly from discrete fracture network (DFN) realisations using the specifications provided in the groundwater flow modelling of the temperate climate conditions (R-09-20). This implies that no modification of properties has been done for glacial stresses and pore pressure variations during glaciation. Heat flow and variable density flow are mentioned but not ice loading.

1.1.2. Models for spatial organization of fractures

The discrete-fracture network (DFN) models provide the underpinning for practically the entire chain of hydrogeological models, which in turn are used to produce parameters for safety assessment calculations including corrosion and radionuclide transport. This places a high demand on the completeness of the DFN analysis, to ensure that a wide enough range of reasonable possibilities are covered to judge safety prior to construction licensing.

Additional information from underground construction might help to reduce the range of plausible models, but this is not assured. For example, simulations of an alternative DFN model for Forsmark (Geier, 2011), in which fractures are spatially correlated to minor deformation zones, indicate that (1) such a model could produce increased flows to deposition holes (by as much as an order of magnitude for the

highest-flow holes) and (2) additional data from tunnels might not necessarily be sufficient to exclude such a model.

The DFN models used for flow modelling in SR-Site only consider the most unstructured form of stochastic spatial organization (random Poisson process), despite suggestions of alternatives from the geological DFN interpretation (for example, heterogeneous fracture intensity based on a gamma distribution, or influence of deformation zones on fracture intensity in nearby portions of a given fracture domain, such as is suggested for Zone A2 in TR 11-01, p. 128-130).

DFN model variants have focused on parametric assumptions regarding the assumed correlation of fracture transmissivity to fracture size. This assumption was indeed important to test, as can be seen from the result that both correlated and uncorrelated DFN give worse results than semi-correlated case. (TR-11-01, p. 609). However these parametric variants do not necessarily bound the uncertainty. As demonstrated by the results of Geier (2011), plausible alternative DFN models could give worse results.

As noted in TR 11-01 (p 130), the hydrological DFN models for the repository volume (fracture domains FFM01 & FFM06) are close to percolation threshold for connected open fractures, with only a small fraction of block-scale simulations showing connectivity. The flow system is described as “compartmentalized.” Considering that this result is obtained for the relatively simple DFN spatial structure considered in SR-Site, the consequences of alternative conceptual models need to be explored.

1.1.3. Alternative parametrizations for major deformation zones

The hydrogeological parametrization of major deformation zones or hydraulic conductor domains (HCDs) is based on a single interpretation of the relation of transmissivity to depth, fitted simultaneously to all of the available transmissivity data for borehole intersections with deformation zones. As discussed further in Section 1.2.2, the basis for this interpretation is arguable. Alternative parametrizations could be developed, e.g., by fitting different trend models to each set of fracture zone separately. Such an interpretation (see Section 1.2.2) may lead to a conclusion that most of the variation for steeply-dipping deformation zones is due to heterogeneity rather than any trend with depth.

The hydrogeological modelling for SR-Site has included a variant that includes stochastic variation of transmissivity within deformation zones, but no variant that allows these zones to have a possibility of high transmissivity at depth. The sparse large-scale testing data data from depth are not sufficient to exclude such a model, which could lead to higher flows through the repository volume.

1.1.4. Demonstration of methods for verifying design premises

The design premises for the repository implicitly require attainment of several objects for which practical methods of measurement have either not been described,

or if they have been described, have yet to be demonstrated as practical. As examples of the first category:

- How will limits of 150 litres (m³) per deposition tunnel be checked after tunnel plugs are emplaced?
- How will leakage past tunnel plugs be monitored?
- How will spalling be detected in deposition holes if not directly visible?

The main example of the second category is the strategy for identifying discriminating fractures in deposition tunnels, particularly extensive sub-horizontal fractures that could intersect multiple deposition holes. The full-perimeter intersection criterion has been described in terms of direct visual observations on tunnel walls, which seems realistic, but how reliable are methods for correlating fractures between deposition holes up to 6 m apart, if the fractures are not perfectly planar or otherwise distinctive? Specifically, can échelon thrust faults be detected?

1.2. Scientific soundness and quality of SR-Site

The key scientific conclusions related to hydrogeology are based in large part on complex models in combination with interpretations of datasets that are sparse for the depths of concern. The models have been developed to a high degree of sophistication and geometric detail in terms of representing the interpretations of hydrological features as well as repository components. For the most part, these models are supported by well-reasoned scientific arguments, and the methods of analysis are credible. However, in some case alternative sources of information and alternative interpretations have been overlooked. The main issues include the following subtopics:

- General understanding of hydrogeologic system
- Interpretation of hydraulic conductor domains and parametrization
- Upscaling methods
- Treatment of channelling

These subtopics are discussed in the following subsections.

1.2.1. General understanding of hydrogeologic system

The fundamental processes governing groundwater flow at sites similar to Forsmark (fractured crystalline bedrock overlain by thin Quaternary deposits, in a humid continental climate with moderate marine influence and proximity to a brackish sea) are generally well understood as summarized in Chapter 3 of the geosphere process (TR-10-48). However, application of fundamental principles to fractured crystalline bedrock does not lead directly to understanding of the groundwater flow system, because the flow system may depend strongly on the heterogeneity and irregularity

of water-conducting features that can be difficult to detect and characterize with a limited number of boreholes.

The discussion of “flow patterns in Sweden” (TR-10-48, p. 43) is excessively dependent on results of regional- and super-regional numerical modelling studies. No observational evidence is cited from subsurface or surface investigations to support the broad conclusions regarding the dominance of local flow cells. A discussion of observations from Finland (the other part of the Fennoscandian Shield, with similar bedrock, topography and climate conditions) is completely lacking. This is a serious omission particularly considering that detailed site characterisation data are available for comparison from the Olkiluoto site in Finland. Results of hydrogeologic investigations from the Canadian Shield (e.g. at the Canadian Underground Research Laboratory in Pinawa, Manitoba) could also be referenced for comparison.

The importance of laterally extensive horizontal fractures in the shallow bedrock as a key controlling factor for groundwater flow at Forsmark is mentioned (TR-10-48, p. 43) without any discussion of the interpreted origins of these fractures, or the reasons why they are so highly transmissive in present-day circumstances. This is important for understanding how these horizontal fractures are likely to respond to future circumstances, such as their potential for closure under elevated vertical stresses which can be expected during future glaciations. The high transmissivities of these fractures have been treated as an unvarying property of the site hydrology for all future conditions, in the models described in the reports R-09-19 through R-09-22.

The discussion of effects of rock stresses on hydrogeology in the geosphere processes report (TR-10-48, p. 45, 3rd paragraph just five lines long) is at a very general level and does not address several key issues that should have been considered (e.g. effects for fracture hydraulic properties of the relationship of stress field orientations to fracture orientations, and stress-dependent fluid storage in the rock). A brief but unsatisfactory argument for neglecting ice-sheet effects on fluid storage is given on p. 48, 1st paragraph, in terms of a hypothetical situation where an increase in pore pressure balances the overburden stress.

The hydrogeological modelling methodology report (R-09-22) presents a very coherent synthesis of how models have been applied and integrated for different scales and climate conditions. The report is generally well-structured and well-argued from a scientific perspective, and directly addresses many of the concerns that are raised by the application of multiple models on different scales and incorporating different subsets of the key processes.

The discussion of hydrogeology and discharge paths in the SR-Site main report takes credit for longer flow paths from the super-regional model (TR-11-01, p. 605). This seems to be consistent with conclusions from SKB's past super-regional modelling, including those cited in TR-10-48, p. 43. However, in reality there is limited knowledge of deformation zones on the super-regional scale and also how these are affected by glacial loading, forebulge effects, etc., so these claims must be viewed with skepticism.

Mechanisms for hydraulic connections from a glacier surface to the base of the glacier should be discussed, if there has been debate (TR-10-49 p. 62). Evidence of such connections, including correlation of glacier movement to surface melting in west Greenland, is not mentioned. The observations of Catania et al. 2008 (as cited

in TR-10-49, p. 69) also seem to support the idea of hydraulic connections from a glacier surface to the base of the glacier. Why do the authors of TR-10-49 imply controversy on this issue (p. 62) if it is not explained? Overall, the understanding and quantification of subglacial hydrology is a weakness in the overall hydrogeological evaluation, so a high degree of uncertainty in the results should be acknowledged.

1.2.2. Interpretation of hydraulic conductor domains

A key feature of the site- and regional-scale hydrogeological models is an exponential decrease in the transmissivity of Hydraulic Conductor Domains (HCDs) as a function of depth. This exponential decrease in transmissivity with depth, together with the “shallow bedrock aquifer” features, helps to produce flow models in which hydraulic head gradients diffuse primarily through the shallow bedrock, with limited effect at repository depths.

The transmissivity-depth function is of the form (R-09-20 p 15-16):

$$T(z) = T(0) 10^{z/k}$$

where $T(z)$ is the deformation zone transmissivity, z is the elevation relative to sea level (RHB 70 datum), $T(0)$ is the expected value of the transmissivity of the deformation zone at zero elevation, and k is a fitted parameter that can be interpreted as the mean depth interval over which transmissivity of a given zone decreases by an order of magnitude. A value $k = 232.5$ m was fitted based on data shown in Figure 1.1.

A single trend model is used for all sets of deformation zones, despite these statements (from R-09-20 p. 15) which suggest hydrologic distinctions among different sets:

The division of the deformation zones into major sets and subsets is useful from a hydrogeological point of view. Most of these structural entities are steeply dipping and strike WNW-NW, NNW and NNE-NE-ESE; one is gently dipping (G).

...

The highest transmissivities within the candidate area, regardless of depth, have been observed among the gently dipping deformation zones. The steeply dipping deformation zones that strike WNW and NW have, relatively speaking, higher mean transmissivities than steeply dipping deformation zones in other directions

When the data for each set of deformation zones are considered separately, the idea of a single trend with depth becomes questionable. For gently dipping zones (set G in Figure 1.1) and the steeply dipping ENE and WNW sets, a decreasing trend with depth is apparent. However, for the NNW set, the highest transmissivity is seen at the deepest measurement point. For the NE set, data are available only over a depth interval of about 100 m; the deepest measurement is intermediate to the two shallower measurements. For the NNE set, three measurements points between -450 m and -800 m were below 10^{-9} m²/s, but the other four measurements, from about -240 m down to -630 m, are remarkably uniform in the range $2-4 \times 10^{-7}$ m²/s. For the NW set there are just three measurements: a single high value at about -100 m, and two lower values near -600 m.

If data from above -150 m (i.e., within the range where tests are likely to be affected by highly transmissive, sub-horizontal sheet joints) are excluded, the gently dipping set is the only set that shows clear evidence of a trend with depth. The ENE set shows an increase in the proportion of tight sections below -600 m. However in the range -100 m to -600 m its dominant characteristic is a very wide scatter of transmissivity values, suggesting a high degree of heterogeneity.

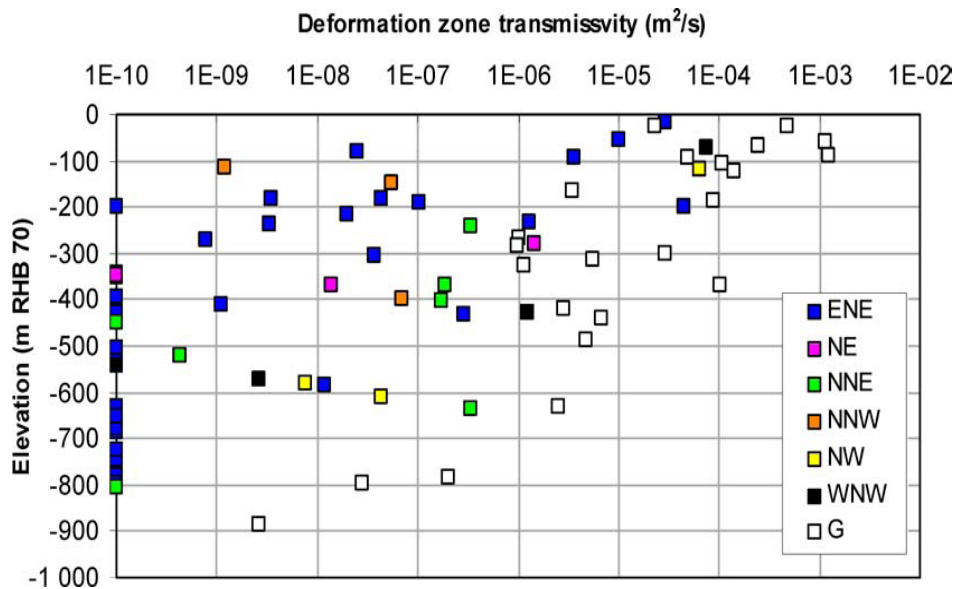


Figure 1.1: Deformation zone transmissivity versus elevation for Forsmark (from R-09-20, Figure 2.4; also in R-09-22 p. 20, Figure 2-6, both based on Figure 5-1 from Follin, 2008). Colored symbols refer to different sets of deformation zones with different nominal strike directions as listed in the legend; G represents gently dipping zones.

Thus the transmissivity data from deformation zones could just as well support an alternative interpretation in which only the gently dipping zones show a regular pattern of transmissivity decreasing with depth, while the steep zones are essentially random (dominated by heterogeneity which ranges over 5 orders of magnitude) in the interval -100 m to -600 m, then predominantly tight below -600 m. However, such an interpretation, or any other alternative to the assumption of a single trend with depth for all zones, has not been tested for SR-Site.

Besides influencing the overall understanding of groundwater flow at the site, insufficiently critical adoption of this single interpretation leads to other poorly supported conclusions, for example this one regarding stochastic, minor deformation zones that intersect the repository in certain realizations (R-09-20 p. 94):

Examination of the particle pathways show that the low F , and t_r values for realisation 5 are associated with a single large, high transmissivity (about $1.0 \cdot 10^{-3} \text{ m}^2/\text{s}$) HRD fracture that extends from the surface and intersects several deposition tunnels near the main tunnel, as shown in Figure 6-20. In reality such a feature would have a depth dependent transmissivity which would reduce the flow associated with it at repository depth.

This is an unsupported statement, as no evidence has been presented for depth-dependent transmissivity in the minor deformation zones which are modelled

stochastically. The idea of depth-dependent transmissivity in these minor zones apparently derives from the inference of depth-dependent transmissivity in the major zones. Arguably such a dependency might exist, but SKB's programme has produced no evidence of it, nor is evidence cited from other subsurface investigations.

As noted by Follin et al. (2008) variability of approximately 2.5 orders of magnitude is observed laterally within individual deformation zones. In the SR-Site model this variability is represented by the simplest possible type of geostatistical model, in which a nugget covariance model is assumed for lateral spatial variability. This implies no spatial correlation of transmissivity above the scale of the finite elements in the model (which are mesh dependent). Tsang et al. (1996) demonstrated that spatial correlation of hydraulic conductivity in deformation zones can lead to large-scale flow channelling that can affect far-field radionuclide transport.

Results of SR-Site modelling (R-09-20 p. 130) further indicate that flows to deposition holes during periods of glaciation are structurally determined by clustering of deformation zones. This underscores the importance of understanding (or considering multiple alternative interpretations for) the hydraulic properties of deformation zones, the effects of glacial loading, and possible repetition of high flux areas during episodic advance and retreat of glaciers.

1.2.3. Upscaling methodology

Upscaling from a discrete representation of bedrock fractures and deformation zones, to yield effective continuum properties for blocks on scales of 100 m or larger, is a central feature of the hydrogeological modelling effort for SR-Site. As noted in R-09-20 (p. 28):

... to model flow and transport on the regional-scale it is often necessary to consider larger-scale bulk properties in the context of an ECPM continuum concept. This requires methods (i) to convert the properties of a network of discrete fractures of lengths less than the continuum blocks into equivalent continuous porous medium (ECPM) block properties, ... and (ii) to represent larger scale features such as fracture zones by appropriate properties in a series of continuum blocks (the IFZ method).

The method for calculation of ECPM block properties from a discrete-fracture network (DFN) model, using the ConnectFlow code, follows a conventional method as described in R-09-20 (p. 30):

ConnectFlow uses six directional components to characterise the symmetric hydraulic conductivity tensor. Using the DFN flow simulations, the fluxes through each face of the block are calculated for each head gradient direction. The hydraulic conductivity tensor is then derived by a least-squares fit to these flux responses for the fixed head gradients.

The method in essence follows that of Long et al. (1982), who showed that valid tensors can be obtained for sufficiently dense and well-connected populations of fractures. As noted in R-09-20 (p. 30), the DFN-ECPM upscaling calculations for Forsmark did not make use of "guard zones." Guard zones, as recommended by Long et al. (1982), are flow simulation domains slightly larger than the block size for which ECPM properties are being calculated (used to guard against overestimation of hydraulic conductivity due to fractures that cut across corners of a block).

The significance of not using guard zones is discussed in R-09-20 based on results for Laxemar, where a similar model showed that the effects were minor. However, as noted on p. 30:

The problem is most significant in sparse heterogeneous networks in which the flux through the network of fractures is affected by 'bottlenecks' through low transmissivity fractures, and is quite different to the flux through single fractures.

Since the water-conducting fracture system is inferred by SKB to be significantly sparser at repository depths for Forsmark than for Laxemar, this issue requires further evaluation.

An additional question, not addressed in SR-Site, is whether an effective hydraulic conductivity tensor is valid for the sparse networks that are inferred at Forsmark. Long et al. (1982) examined this in terms of goodness-of-fit statistics for the fitted hydraulic conductivity tensors. Goodness-of-fit statistics for the ECPM tensors computed by ConnectFlow for Forsmark have not been reported. If the fits are poor, this implies a system in which the ECPM upscaling will result in more uniform connectivity than the underlying DFN model, resulting in a less heterogeneous flow system with distributed rather than discrete pathways for transport.

Upscaling of the deformation zones (HCDs) is handled in ConnectFlow by a different method as described in R-09-20 (p. 41):

The IFZ method identifies which elements are crossed by a fracture zone and combines a hydraulic conductivity tensor associated with the fracture zone with a hydraulic conductivity tensor for the background stochastic network. For each element crossed by the fracture zone the following steps are performed:

- 1. The volume of intersection between the fracture zone and the element is determined.*
- 2. The hydraulic conductivity tensor of the background rock is calculated in the coordinate system of the fracture zone.*
- 3. The combined conductivity tensor of the background rock and the fracture zone is calculated in the coordinate system of fracture zone.*
- 4. The effective hydraulic conductivity tensor that includes the effect of the fracture zone is determined in the original coordinate system.*

This method is appropriate for accounting for the contributions of transmissive features that are large enough to cut across a given ECPM block. The scientific consistency of this approach has been adequately demonstrated, for such cases.

Block-scale porosities are calculated in ConnectFlow as a weighted sum of the pore space contained in connected fractures and deformation zones. The weighting is proportional to transmissibility (transmissivity times flow length of each feature). This is appropriate for transport calculations, as it gives an approximation of the fraction of porosity that is most likely to be encountered by solute moving through the dominant flowing features that are represented by an ECPM block. The choice of fracture aperture values, which are needed to calculate the pore volume of a given fracture, is a separate issue as discussed in Section 1.4.1.

The DarcyTools modelling software, which has been used for simulations of the construction & operation phase and for future permafrost and glaciation conditions (R-09-19 and R-09-21), uses a different method of upscaling DFN properties which is mathematically equivalent to that derived by Oda (1985). For large, through-going features it gives the same results as the IFZ method, but for smaller fractures it leads to an overestimation of the contribution to effective block-scale hydraulic

conductivity. This method has not been used for simulations with DarcyTools for SR-Site, according to R-09-19 and R-09-21. Instead, ECPM properties have been imported from ConnectFlow. This is an improvement over the methods used in previous applications of DarcyTools. However it is still subject to the issues described above, regarding DFN upscaling methods used in ConnectFlow.

The DFN models developed during SDM-Site are defined only for fracture domains covering a small part of the regional-scale model domain. For the hydrogeological base case considered in R-09-19 through R-09-22, the rock mass in the remainder of the regional domain is represented by a homogeneous continuum (plus regional deformation zones which are represented by the IFZ method as described above).

The significance of using a homogeneous continuum on the regional scale was investigated by an “extended spatial variability case” based on DFN from investigations at SKB's SFR site (R-09-20 p. 68-69). This DFN model was assumed to be valid throughout all portions of the regional-scale model domain that were not covered by the DFN models from SDM-Site. Although the applicability of the DFN data from the SFR for such a wide area is certainly doubtful, this gives a reasonable way of generating a stochastic ECPM for scoping the effects of block-scale heterogeneity.

The conclusion, according to R-09-20 p. 68, is that the homogeneous CPM used in the base case “*greatly reduces the effect of outcropping sub-vertical deformation zones on particle exit points.*” In other words, this feature of the base-case hydrologic model tends to predict more dispersed discharge to the biosphere than is predicted by a model that incorporates a more realistic degree of variability throughout the regional-scale domain.

In simulations using DarcyTools (R-09-21), an ECPM representation is used for the rock containing the repository. The consequences of this representation for calculating flows to the repository are discussed in R-09-22 (p. 113). As seen in Figure 1.2, differences are seen in the distribution, primarily in terms of lower variance and a reduced fraction of deposition holes with Darcy flux higher than 10^{-5} m/yr. As noted in R-09-22, the tails representing the high values of Darcy flux are similar despite the differences for lower values. However, the most extreme flows, to the top one percentile of deposition holes (as represented by the blue symbols close to the top edge of the plot) are underpredicted by a factor of 10 to 100, by the ECPM representation.

The upscaling for the regional-scale ECPM model domain omits fractures with radii smaller than 5.6 m, but these are kept in site-scale and repository-scale flow. The practical reasons and consequences of this difference are well explained in R-09-20, so this is not an issue of concern for the safety assessment.

A novel “Equivalent Discontinuous Porous Medium” (EDPM) approach is discussed in R-09-22 (Chapter 4 and p. 109), with the suggestion that this is a preferable to the ECPM approach when inflow to individual deposition holes are considered in a low permeability environment. Further scientific scrutiny of this approach is needed to make sure that the improvements claimed are not simply artefacts of insufficiently accurate local solutions in a strongly heterogeneous ECPM model.

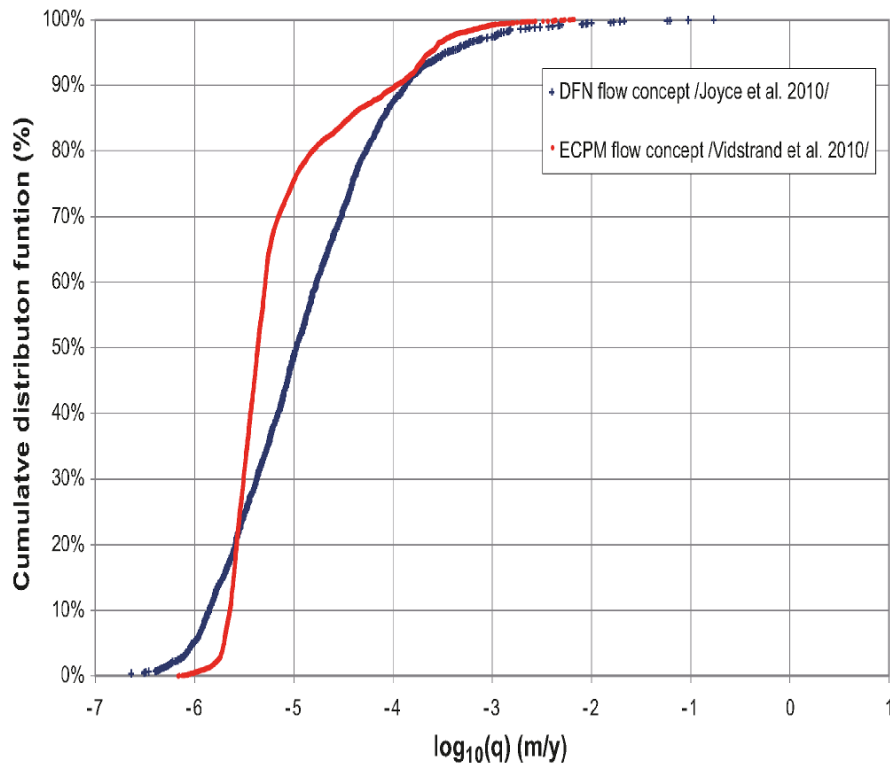


Figure 1.2: Cumulative distributions of Darcy flux at deposition hole positions for future temperate climate conditions, comparing results obtained from the simulations conducted with DarcyTools (ECPM representation) on a super-regional scale (red curve), and results from the simulations conducted with ConnectFlow (DFN) on a repository scale (blue curve). From R-09-22 (Figure 7-3).

1.2.4. Treatment of channelling

Flow channelling is discussed in TR 11-01 and has been incorporated in past transport simulations for SDM-Site in terms of a “channelling factor” which effectively reduces the transport resistance of flow paths by a factor of 0.1. This approach is intended to account for the reduction in area that is available for matrix diffusion from fractures.

In SR-Site it is further argued (p. 138) that taking account of channelling by this approach is conservative since it does not take credit for the radial matrix diffusion from effectively pipe-like channels, or diffusion into stagnant zones of a fracture plane in contrast with the one-dimensional geometry of diffusion from a planar fracture. However, this argument overlooks the general scientific consensus (e.g. as documented by the RETROCK project) that channels in fractures tend to be broad in relation to the aperture. Hence the benefits of increased dimensionality for diffusion would be achieved only near the edges of a channel.

The main problem with the treatment of channelling in SR-Site, however, is that this is considered only as a modification to a network model that is derived and calibrated in terms of a conceptual model of interconnected plate-like fractures, with uniform flow properties across each plate. Different results might be obtained if

channelling was assumed in the calibration process, as such a model would have different connectivity characteristics for a given set of fracture parameters.

1.3. Adequacy of relevant models and data

Sources of information for key datasets, derivations of parameters, and mathematical models and assumptions are for the most part adequately documented to allow review. A few problems were encountered which are discussed in Section 1.6 in terms of transparency and traceability issues.

The use of multiple types of hydrogeological models (different software, scales, and mathematical conceptualizations) to account for different issues of concern for long-term site evolution leads to a need to manage and track data that are passed between models. For example, DarcyTools and ConnectFlow both use ECPM hydraulic conductivity fields that are calculated within ConnectFlow, but must be exported to DarcyTools. Flow calculations using ConnectFlow for detailed representations of the repository in the glacial case (R-09-20 p. 74-76) in turn depend on pressure & salinity fields which are imported from the DarcyTools model (R-09-21; R-09-22 p. 43).

In addition, use of multi-scale models with the ConnectFlow concept requires linkage between CPM/ECPM and DFN parts of the model (R-09-20 p. 32). This requires implementation of “internal boundary conditions” to ensure continuity of pressure and conservation of mass. These conditions appear to be appropriately handled, according to the descriptions, but the internal exchange of these types of data within model makes it more difficult to understand the characteristics of the individual parts of the models, for review purposes.

The key aspects of the multi-scale modelling approach used for the temperate period are summarized in Figures 1.3 and 1.4. Modelling time scales, flow and transport models, representations of repository components, and key input/output for each scale of model are summarized succinctly in Tables 3-1 and 3-2 of R-09-20.

During particle-tracking to predict properties of transport paths, it was found (R-09-20 p. 43) that some particles exit the vertical sides of the repository-scale model. These were handled by restarting these particles from corresponding positions in the **site-scale model**. Performance measures such as travel time are then calculated as the cumulative travel-time along both legs of the path. While this approach is conceptually correct, it requires an additional level of bookkeeping which is not directly reported. Review of this and other ways in which data are exchanged between models on different scales may be worthwhile for subsequent, detailed review.

The two primary models (ConnectFlow and DarcyTools) differ their treatment of the physics of mass transfer of salinity between matrix and fractures and their representation of dispersion (R-09-22, p. 46). The implementation in DarcyTools assumes that macrodispersion can be accounted for as a combination of heterogeneity in the ECPM together with advection and diffusion, and that dispersion on the sub-grid scale due to smaller-scale flow-field heterogeneity can be neglected. This assumption should be verified by reference to experiments on relevant in fractured rock.

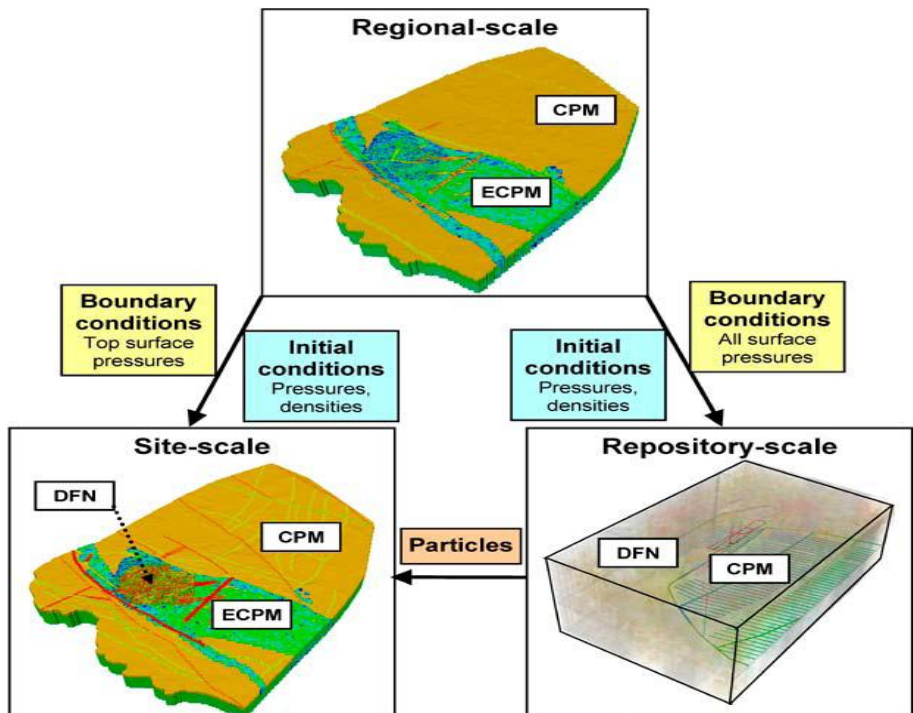


Figure 1.3: Illustration of the concepts of model scales, embedding, and the transfer of data between scales (from R-09-20, Figure 3-9).

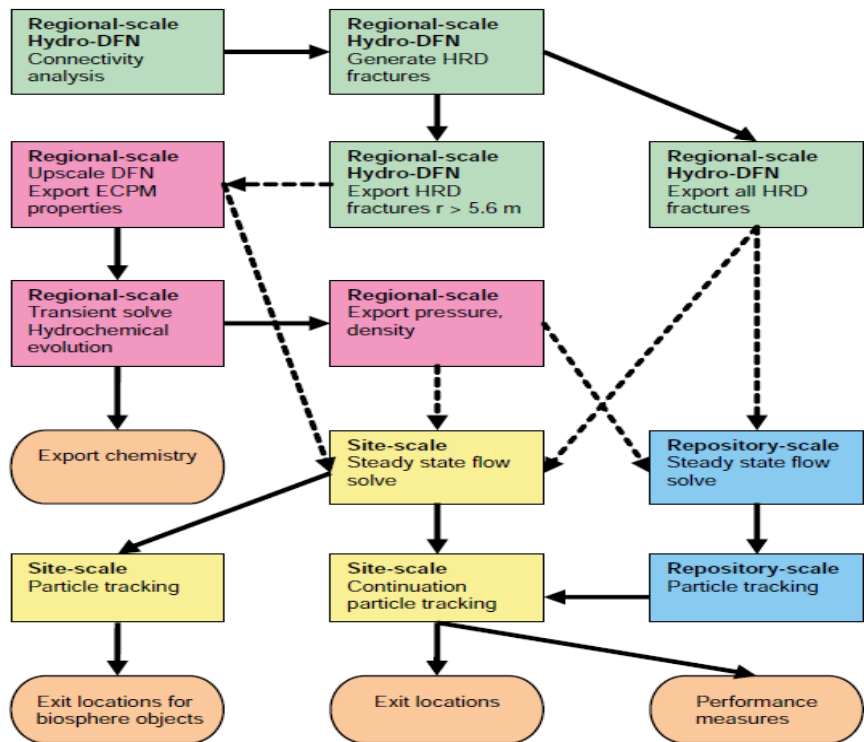


Figure 1.4: Modelling processes. Fracture generation is shown in green, regional-scale processes in pink, site-scale processes in yellow and repository-scale processes in blue. Outputs are shown in peach. Solid arrows indicate the modelling workflow within a scale and dotted arrows indicate a transfer of data between scales. From R-09-20, Figure 3-10.

1.3.1. Particle tracking methods

The algorithms used for particle tracking vary in their representation of macrodispersion, depending on the type and scale of model. In ConnectFlow (R-09-20 p. 34) dispersion is not simulated for portions of particle trajectories that pass through ECPM or CPM blocks. In other words, these parts of the trajectories are fully deterministic for a given flow-field.

However, within DFN portions of a model, a type of macrodispersion can result from probabilistic allocation of particles to outflowing branches of a fracture intersection. The algorithm allocates particles in proportion to the mass flux, which is equivalent to an assumption of complete mixing in the fracture intersections. This is likely justifiable for the low fluid velocities that are expected for post-closure temperate conditions. However, applicability for faster flows (such as may arise during glaciations) should be checked in terms of the Peclet number for flow through the fracture intersections (Berkowitz et al., 1994).

No dispersion is assumed to occur within fracture planes regardless of size (not justified in this report although it is supported for the case of variable-aperture fractures by previous SKB research by (Painter, 2006). No tortuosity of transport paths is assumed in the fracture plane; this is likely conservative.

According to R-09-20 (p. 79 ff) some particles do not reach the surface, either due to getting stuck in low-velocity areas of the calculated flow field or due to exiting a side boundary of the model. Particle tracks in some cases (e.g. R-09-20, p. 102, Figure 6-25) appear to show strong effects of the diagonal gridding scheme that is used in deformation zones. This might add artificial effects of tortuosity to the computed residence times and transport resistances, but the net effect is perhaps not significant since other (physically realistic) sources of tortuosity in fracture planes have been neglected.

1.3.2. Abstraction of safety-assessment parameters

Formulae for calculating performance assessment parameters from the flow models and particle tracking output are described in R-09-22 (p. 30, p. 40).

For a discrete model for sparsely fractured rock such as is apparently encountered in the repository target volume at Forsmark, Darcy flux and the equivalent flowrate, Q_{eq} , are both in some sense nonphysical quantities as they depend on volumetric averaging assumptions and/or diffusion parameters. While these parameters are needed as part of the interface to SKB's transport models, presentation of DFN results exclusively in these terms is an obstacle to understanding physical meaning of the results. The physically valid quantities in a DFN model are the mean water velocity in the fractures, or flux density per unit fracture width. Solute exchange with a leaking or corroding canister is presumably related to the ratio between the water velocity and the diffusion through water in the fracture. Presentation of the quantities that can be calculated directly from the DFN models would be helpful to present for better understanding of the results.

The formula for F factor (R-09-22 p. 40) includes two parameters for each path segment which are not clearly defined: Flow width w_j and flow segment length. How are these defined for the general case where flow in the fracture plane is between

intersections with two other fractures that are not parallel to each other, and which may have different intersection lengths? How are these quantities defined for cases in which three fractures intersect at a single point? Illustrations to explain such cases would be useful as additional information for understanding the results.

When there are multiple fractures intersecting a deposition hole, Q_{eq} for the Q1 path is calculated as the sum of contributions of individual fractures ($Q_f/\sqrt{a_f}$), divided by the deposition hole length (R-09-22 p. 40). In such cases, is each of these fractures then also used as a source for particle tracking? Different units are used for the initial Darcy flux depending on the type of flow path, in order to determine whether to launch particles – does this quantity have a consistent physical meaning?

1.4. Handling of uncertainties

Although many relevant uncertainties related to hydrology have been identified, analysed, and discussed in sufficient detail, a few areas where further analysis is needed are discussed in the following subsections

1.4.1. Uncertainty in fracture transport aperture

In the approach used for data analysis and groundwater flow modelling for SR-Site, the discrete-fracture network model is parametrized in terms of fracture transmissivities rather than fracture apertures. This is reasonable as fracture transmissivity is more directly related to what can be measured by hydraulic tests in boreholes. However, fracture apertures are needed to relate groundwater flux to advective velocities and water residence times for transport modelling.

According to R-09-20, two different mathematical models relating transport aperture e_t to fracture transmissivity T have been used. In the hydrogeological base-case model, the following relationship is used (R-09-20, Equation 6-1):

$$e_t = 0.5T^{0.5}$$

The authors note that the coefficient 0.5 has been rounded from 0.46 (the value used in SDM-Site (Follin, 2008)). For sensitivity studies, a second relationship based on a compilation of Swedish tracer test data by Hjerne et al. (2010) has been used (R-09-20, Equation 6-2):

$$e_t = 0.28T^{0.3}$$

These relationships are plotted in Figure 1.5 together with the “cubic law” which is the expected relationship between aperture and transmissivity for laminar flow of water through an idealized parallel-plate fracture which has a perfectly uniform aperture. It is apparent that the Hjerne et al. (2010) model gives the highest apertures, particularly for the higher transmissivity fractures, while the cubic law gives the lowest apertures. The rounding of the base-case model's coefficient from 0.46 to 0.5 is seen to have very little effect.

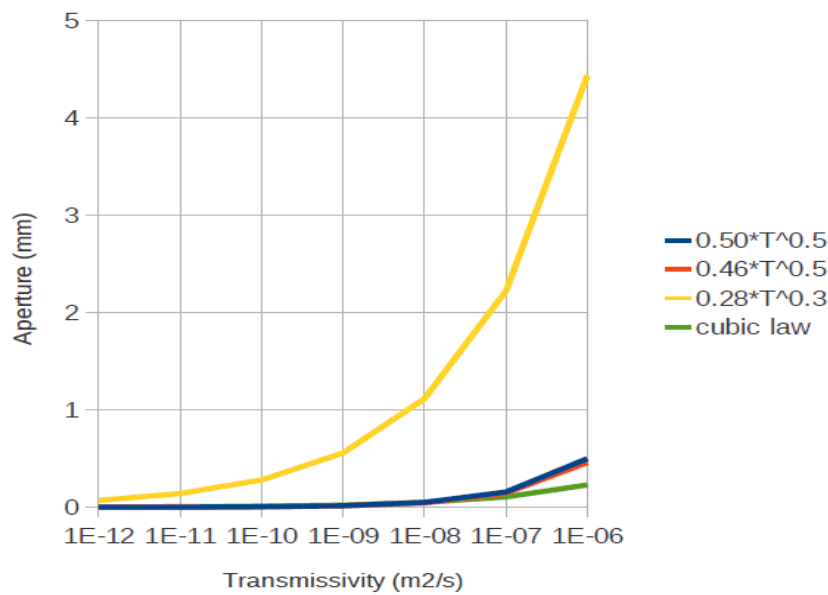


Figure 1.5: Comparison of alternative relationships between fracture transmissivity and fracture transport aperture.

Considering that both the base-case model and the Hjerne et al. (2010) model are empirical models fitted to different sets of experimental data, it is doubtful that these bound the range of reasonable possibilities. The cubic law gives consistently smaller apertures than either of these empirical models, and thus yields shorter water residence times for a given transmissive network. On the other hand, the cubic law also gives a higher ratio of wetted surface per unit volume water in the fractures, which offsets the effect of shorter travel times in terms of F factor (transport resistance) calculations.

Other alternative relationships could include stochastic relationships between transport aperture and transmissivity (rather than a perfect correlation), or different relationships for different fracture sets depending on their orientation.

The Hjerne relationship gives about an order of magnitude increase in median water residence times, compared to the hydrogeological base case (R-09-20 p. 94). Thus the consequences of assuming one model or the other for transport aperture can significantly affect predictions of groundwater velocities. The sensitivity to a wider range of alternatives, including stochastic relationships, should be explored to determine if there are plausible relationships that could lead to an effect on residence times greater than the observed order-of-magnitude effect.

1.4.2. Uncertainty in flow model

In addition to uncertainties in the parametrization of major deformation zones (HCDs), there are residual uncertainties related to the derivation and parametrization of the DFN component model. The SR-Site main report claims (TR 11-01, p. 128) that there is high confidence based on consistency between different types of hydraulic data. However, it is also noted that flow rates measured by tracer dilution method are sometimes much higher than expected (TR 11-01, p. 128).

R-09-20 (p. 26) mentions comparisons against three sets of confirmatory data:

- transient, large-scale cross-hole (interference) test responses,
- steady-state, natural (undisturbed) groundwater levels in the uppermost 150 m, and
- hydrochemical observations in deep boreholes

However, the number of transient, cross-hole tests were limited (number of data and sensitivities should be discussed), as were first-strike, undisturbed groundwater pressure measurements from the deep bedrock.

The use of hydrogeochemical data for reference water fractions to check the site-scale model calibration is innovative but leaves questions regarding the significance of deviations which are observed both in terms of reference water fractions and the depths at which transitions are observed. The latter are perhaps the most important for checking the understanding of the site-scale flow system, but receive little discussion and tend not to be highlighted by the methods of presentation.

R-09-20 (p. 26) further notes that:

[T]he performance of the groundwater flow model, which was based on equivalent continuous porous media (ECPM) properties, was slightly improved if the anisotropy of the horizontal to vertical hydraulic conductivity ratios of the upscaled values for both the Quaternary deposits (HSD) and the fracture domains (HRD) were increased compared with the upscaled values derived from the initial structural-hydraulic settings.

This implies that the model was adjusted to improve the fit, rather than simply using the data to test the model. The way in which this adjustment was performed is not clearly reported in the documents covered by this review.

1.4.3. Use of stochastic realizations and variants

Multiple stochastic realizations and hydrogeological model variants have been used to investigate key uncertainties. Ten realizations of the model with semi-correlated size-transmissivity model for DFN fractures and stochastic properties in the hydraulic conductor domains were propagated through the safety assessment chain including probabilistic central corrosion cases, in addition to a single DFN realization which used laterally homogeneous HCD properties. (Data Report Section 6.7; TR-11-01 p. 654-655). Additional model variants were used to test the consequences of adding additional “possible” deformation zones, the effects of varying tunnel properties, the effect of boreholes arising from human intrusion, and effects of glacial conditions including effects on tunnel properties under glacial conditions. A concise summary of the cases analysed for the temperate case and glacial case is given in Table 4-1 of R-09-20.

Glacial case variants with elevated EDZ transmissivity are found to be significant for Q2 & Q3 flows (R-09-20 p. 122). A variant that includes a transmissive path through the crown space of tunnels reduces Q2 but enhances Q3. Little effect on Q1 is seen for either EDZ or crown space variants. Similar effects are seen for EDZ properties in combination with the temperate case (R-09-20 p. 114).

Simulations of the construction and operation phase considered three different levels of grouting efficiency (R-09-19; R-09-22 p. 46-47). However only homogeneous grouting efficiency is considered (or homogeneous grouting to one level in the rock mass, and to another level in deformation zones intersecting the repository). Heterogeneous grouting might not be important for the major predictions of R-09-19, such as overall drawdowns of meteoric waters, upconing, and resulting changes in water chemistry around the repository. However, it might contribute to heterogeneity of flows to deposition holes during the resaturation period.

In the glacial case calculations reported in R-09-21, the glacial case without permafrost produces the largest hydraulic gradients at the ice sheet margin, hence the greatest effects on Darcy flux and fracture (advective) salinity at repository depth. All variants are based on a uniformly advancing ice sheet. One question to consider for further review is whether a lobed glacial front in combination with localized absence of permafrost could yield more severe consequences in terms of hydraulic gradients and focussing of flow through the repository.

A discontinuous permafrost layer ahead of a glacier is considered in R-09-21, using probable locations for taliks (unfrozen spots in the permafrost layer) which are estimated from a forecasted landscape development model for Forsmark. A question is whether talik locations can be sufficiently well predicted by this approach to bound the uncertainties, or whether a more stylized approach should be used to complement this. Uncertainty in the occurrence of taliks is discussed in the climate report (TR-10-49) but only in generalized terms.

1.5. Safety significance

Are the safety functions, indicators and criteria adequately defined and meaningful with respect to geosphere variables that can be measured or reliably calculated?

Safety functions, safety function indicators and safety function indicator criteria are summarized in Figure S-7 of TR-11-01 (p. 26). Safety functions that are closely related to hydrogeological interpretation and modelling are discussed in order of their appearance in this figure.

1.5.1. Safety Function R1. Provide chemically favourable conditions

The chemically favourable conditions (Eh; salinity; ionic strength; concentrations of HS^- , H_2 , CH_4 , organic C, K^+ and Fe; pH; Cl^-) are all functions of flow system in combination with chemical transport and buffering reactions in the natural system.

Reducing conditions (R1a) are judged to be maintained (TR-11-01 p. 29) on the basis that “*Local, temporary penetration of oxygen to repository depth cannot be excluded during hydrologic transients caused by passage of an ice sheet margin but the effects are too small to influence safety.*” Key hydrologic issues that relate to this safety function thus concern the duration and magnitude of hydrologic transients associated with the passing of an ice sheet margin.

The concept of flow channelling may be significant for assessing this safety function, since channelized flow may enhance the penetration of glacial meltwaters with less chance for buffering by the rock matrix. In SKB's Site Descriptive Model, channelling is applied as a factor for transport after deriving and calibrating a HydroDFN based on assumption that the full fracture plane participates in flow. Would calibration of a channelized model lead to very different results for penetration of glacial meltwaters to repository depths?

1.5.2. Safety Function R2. Provide favourable hydrologic and transport conditions

Both of the subcriteria for this function, to provide high transport resistance (F) in fractures and low equivalent flow rates Q_{eq} at the buffer/rock interface, are direct functions of the hydrogeological model and especially the DFN component that represents the relatively unfractured rock between deformation zones.

This issue encompasses processes that could affect the DFN network and its interactions with the rock matrix, over long time periods that must be considered for safety assessment. Matrix-fracture interaction on large time scales as well as EDZ connectivity effects and evolution of the excavation-influenced zones are both relevant. Key questions for a comprehensive review include:

- ▲ Is there sufficient understanding and/or exploration of how EDZ affects local connectivity, as the EDZ and excavation-influenced zone evolve during construction, operation, and post-closure stages?
- ▲ Are there plausible scenarios that could affect DFN connectivity as well as flow, and if so have these been adequately considered?

The effects of the climate phases considered in SR-Site on Darcy flux to deposition holes are well summarized by a figure from R-09-22 which is reproduced in Figure 1.6. From this it is seen that the situation of greatest concern that has been evaluated so far is glacial advance without permafrost, followed by glacial permafrost situations.

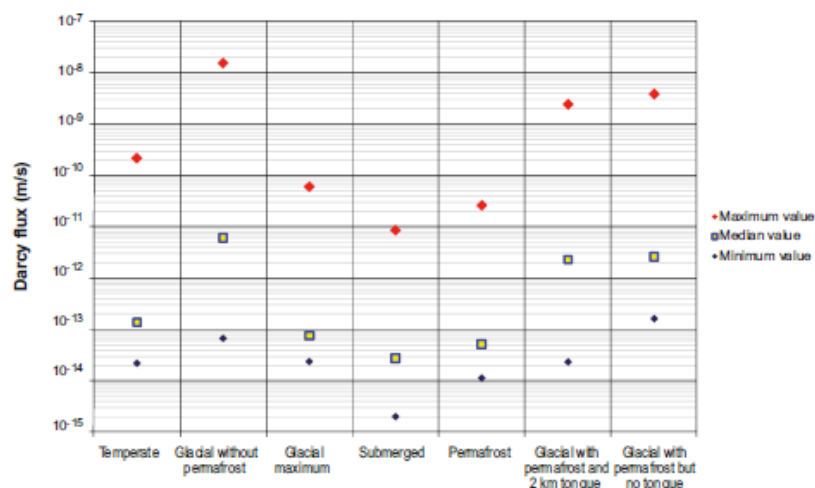


Figure 1.6: Effect of climate situations on Darcy flux. From R-09-22 Figure 6-20.

1.5.3. Safety Function R3. Provide mechanically stable conditions

Subcriteria for this safety function include limited groundwater pressure which is a function of groundwater flow but primarily a function of overburden stress. The other subcriteria (shear movements and shear velocity at deposition holes) are primarily a function of earthquake scenarios which are at best indirectly related to groundwater flow. However, there is overlap with hydrogeology in terms of methods for avoiding large fractures and minor deformation zones.

1.6. Quality in terms of transparency and traceability of information

Transparency and traceability in hydrogeological modelling for SR-Site suffer from many small problems which, when taken individually, generally do not detract significantly from confidence in the results of the calculations, but collectively lead to concerns that should be addressed. The following are noted as examples.

TR 11-01 (p 137) states that “Less than 4% of realizations below 400 m exhibit connectivity of any kind,” but does not indicate what block scale this finding pertains to.

According to R-09-20 (p. 41) a minimum block conductivity and porosity is set for any elements that have zero values of these properties following the fracture upscaling and IFZ methods. It is stated that “*appropriate minimum properties were derived in the SDM Hydro-DFN studies by calculating the minimum values seen when the DFN is truncated only at very small fractures relative to the block size, and so are essentially free from the truncation effect.*” However, these minimum values are not stated.

According to R-09-20 (p. 26) the performance of the groundwater flow model based on ECPM properties,

was slightly improved if the anisotropy of the horizontal to vertical hydraulic conductivity ratios of the upscaled values for both the Quaternary deposits and the fracture domains were increased compared with the upscaled values derived from the initial structural-hydraulic settings.

However, the magnitude of this adjustment is not documented in this report nor in R-09-22.

According to R-09-20, the base-case model relating transport aperture e_t to fracture transmissivity T is (Equation 6-1):

$$e_t = 0.5T^{0.5}$$

The authors note that the coefficient 0.5 has been rounded from 0.46 (the value used in SDM-Site (Follin, 2008)). However, R-09-22 (p. 24) gives the original expression without rounding the coefficient:

The values of the parameters a and b in Equation 2-5 used in SDM-Site are defined in /Dershowitz et al. 2003/, where a = 0.46 and b = 0.5. /Stephens et al. 2007/ provide values of the geologic thickness of all deterministically modelled deformation zones.

and does not mention that the coefficient was rounded to 0.5 for the SR-Site models.

R-09-20 further states that:

The kinematic porosity of the deformation zones was not investigated. In the groundwater flow modelling, values of the kinematic porosity were calculated from the ratio between the transport aperture and the geological thickness. The transport apertures were calculated from the transmissivities of the deformation zones (see Eq. (2-1) in /Follin 2008/ and Eq. (3-17) in Section 3.2.2) and the values of the geologic thicknesses were provided by /Stephens et al. 2007/.

However the referenced Equation 3-17 does not exist in this report, and Eq. 3-5 on p. 41 is introduced as:

The transport aperture, e_t , of each fracture that represents a DZ is calculated as:

$$e_t = \Phi b$$

where Φ is the porosity and b is the thickness of the deformation zone at that point, as specified by the geologists.

which appears to be a case of circular reasoning. It can further be noted that geological thicknesses do not always correspond to the hydrologically active portions of deformation zones. Correct equations are eventually given on p. 30 of R-09-20.

Follin (2008, p. 32) gives the original form of the equation:

For the sake of the SDM, the kinematic porosity, n_e , was derived based on the underlying hydrogeological DFN calculated element-by-element as the total connected volume divided by the element volume. The fracture volume for an individual fracture was calculated as the fracture area within an element multiplied by the transport aperture, and this is modelled based on Äspö Task Force 6c results /Dershowitz et al. 2003/, which assumes a direct correlation between the transport aperture e_t and the transmissivity T , such that:

$$e_t = 0.46 T^{0.5}$$

But then go on to say (bold text added):

Although this approach provides a direct link between the assignment of kinematic porosity in the ECPM model and the underlying DFN model, it relies on several approximations, including that the full fracture surface area contributes to advection and that the contribution to porosity of fractures below the truncation of fracture sizes in the regional DFN model is not significant.

Hence, the derived kinematic porosity using Eq. (2-2) was used as an initial guess to the calibration, and adjustments were made as part of the calibration to help inform the description of the fracture transport properties.

This leaves a question as to whether these “adjustments” are reflected in SR-Site calculations.

As a separate issue, in the discussion of boundary conditions for the SR-Site temperate-stage hydrogeological model (R-09-20 p. 55), the following is stated [with comments added in bold-face in square braces]:

The boundary conditions used for SR-Site were the same as those used for SDM-Site. They consisted of a recharge-discharge boundary condition [with what values?] on the top surface and no flow through the sides [how justified?] and bottom of the model. The bottom of the model also had a hydrochemical boundary condition set to the initial values of the reference water mass fractions [not given here, but found in Section 6.2]. The reference water mass fractions on the top boundary varied with time according to the elevation of shoreline with regard to the topography of the ground surface [where found?]. The initial conditions were also the same as those used in SDM-Site, except as noted in Appendix C.

As a self-standing reference document for SR-Site, this report should reiterate all values that are carried forward from previous site-modelling work, rather than

referring back to previous reports which include many aspects that have not been carried forward to SR-Site modelling.

1.7. Feasibility of construction, testing, implementation and operation of repository components

1.7.1. FPC and EFPC criteria

The key issue related to construction feasibility for the DFN model concerns the implementation of the full-perimeter intersection criterion (FPC) and the extended full-perimeter criterion (EFPC), as described by Munier (2010).

The implementation of the hydrogeological model in SR-Site does not account for application of the FPC or EFPC criterion. Hence ensemble statistics are calculated over the same set of 6,916 deposition hole positions for all realizations and model variants (R-09-22 p. 41). Positions that would be rejected based on FPC or EFPC are sorted out later:

An algorithm for analysing the deposition holes according to the FPC and EFPC was implemented in ConnectFlow. This was used to flag deposition holes that may be excluded due to these criteria, but they were not actually excluded in the flow or particle tracking calculations. For the purposes of the algorithms, full-perimeter indicated an intersection between a fracture and all four side edges of a deposition tunnel or a deposition hole. Also, in the implementation of the FPC, the fracture was not hypothetically extended when considering intersections with deposition holes, i.e. the fracture needed to actually intersect the deposition hole as well as the full perimeter of the deposition tunnel.

This implementation differs from the approach of Geier (2011) which mimicked an adaptive emplacement strategy conditioned on each realization of the DFN model, so that deposition holes are shifted along the tunnel when FPC fractures are encountered. The consequences of this difference is probably minor, as the presence of fictitious deposition holes that would be rejected with a full implementation of the FPC affects inflows only slightly.

The main results of the effects of applying FPC and EFPC in the SR-Site model (R-09-20 p. 88), in terms of flows to deposition holes, follow from the assumed (semi-)correlation of transmissivity to fracture size. The outcome may be less good if transmissivities are uncorrelated or less strongly correlated to fracture size.

The reporting for SR-Site in places assumes benefits from application of the FPC and EFPC which have not yet been proven. For instance, (R-09-20 p. 95) states:

Similarly, many of the high U_r values for realisation 9 are associated with a single large HRD fracture ...the fracture is gently dipping and intersects a large number of deposition holes, one deposition tunnel and a large number of other highly conductive features, such as deformation zones. Because it intersects the deposition holes it has a particular effect on the Q_1 release locations. In practice, the affected deposition holes would be eliminated by the application of the FPC and EFPC due to the large number of adjacent deposition holes intersected by this fracture.

While such effects are hoped for as a consequence of applying the FPC and EFPC criteria, as a side effect of screening deposition hole locations for earthquake shearing risk, they have yet to be demonstrated.

Some confusion about the motivation for the FPC and EFPC criteria is evident on p. 117 or R-09-22, where:

it is noted that the "FPC or EFPC" criterion also has relevance for reducing risks associated with e.g. earthquakes; hence, inflow rejection criteria alone may not be sufficient to identify unsuitable deposition hole positions. A combination of both types of criteria likely needs to be considered in the future.

In fact earthquake risk is the primary criterion, and hydrogeological issues are secondary. However application of this criterion, in conjunction with additional deposition-hole inflow criteria as discussed in R-09-22 (p. 109), gives promise of reducing flows that affect safety, as well as minimizing earthquake shearing risk. The results shown in Figure 7-1 of R-09-22 are promising as a basis for establishing hydrogeological criteria for abandonment of deposition holes.

A practical question that should be answered for license application review is what criteria are actually planned for implementation. Without clarification on this issue, from a regulatory perspective it is difficult to rely upon implementation of any non-obligatory ideas.

A potential obstacle to implementation of these suggested hydrologic criteria might be if the calculated inflows are too large in relation to reality (TR 11-01, p. 302). This could affect the usefulness/efficiency of an inflow-based rejection criterion.

1.7.2. Resaturation

Resaturation of the repository is a second issue for which hydrogeology is a major controlling factor, and which requires further demonstration in terms of practicality. Given the interpretation of the repository target volume at Forsmark as extremely tight, with many deposition holes predicted to be not connected to any flowing fractures at all, and generally low flows to deposition tunnels, it seems possible that the period to achieve saturation of backfill and buffer could be much longer than planned, and that this process could be heterogeneous rather than uniform across the repository.

In TR-11-01 (p. 315), an assumption is that O₂ following closure is uniformly divided among canisters. What happens if the tunnel saturates from one end, so that some canisters are exposed to gaseous-phase O₂ for a longer period.

Only cases of uniform geometry are considered in TR 11-01 (p. 299). This may be reasonable since the focus is on drawdown/upconing to the repository as a whole, but this may affect inflows to individual deposition holes.

R-09-19 concludes that it will take several hundred years for the repository to reach full saturation. In R-09-22 it is argued that this is a short period compared with the length of the temperate period (on the order of 10,000 years), so this initial period of unsaturated conditions is of minor importance. However, if the continuum models overpredict flow into the repository (as suggested by R-09-22, p. 55), the time for resaturation could well be longer. Has this been scoped with alternative models?

2. Recommendations to SSM

2.1. Recommendations for clarifications

2.1.1. Topics for submissions

Request goodness-of-fit statistics for the ECPM tensors computed by ConnectFlow for Forsmark.

Request ECPM tensor data passed from ConnectFlow to DarcyTools.

Request pressure & density data passed from regional-scale model to site-scale model

What happens to particles that do not discharge from the surface boundary of the flow models? How are they accounted for?

What are SKB's reasons for choosing the aperture-transmissivity models that are utilized and not considering a broader range, such as the bounding case of the cubic law? Have aperture-transmissivity correlations with a stochastic component been considered and/or ruled out as cases of interest?

How are flow path widths and flow segment lengths defined in DFN particle tracking results from ConnectFlow?

2.1.2. Topics for discussion

What are SKB's plans for demonstrating methods for verifying achievement of the design premises in the repository?

What is the effect of no-flow boundary conditions on the calculated inflows to the deep repository and an extended SFR, during a period of simultaneous operation? From Figure 2.1 it can be seen that, in the model of this situation, drawdowns up to 10% of the maximum drawdown extend to the north and east boundaries of the model domain. How significant are the reductions in inflows due to this artificial restriction at the model boundary?

Should the extended spatial variability case be propagated throughout the safety assessment, as it appears to be more realistic and produces shorter discharge paths and lower F values in the late temperate period.

What is the importance of lower resolution of the structural model in offshore areas; are there no variants to test this?

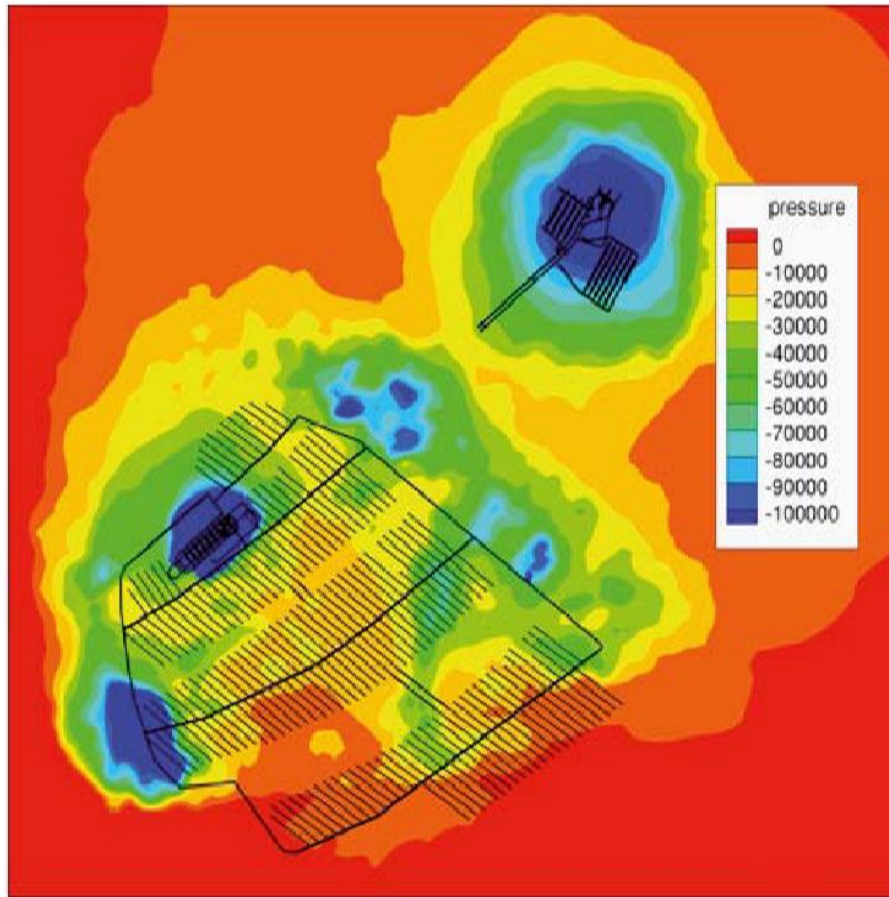


Figure 2.1: Pressure interference (Pa) at -150 m elevation for a simultaneous operation of an extended SFR and a deep repository in the target volume for the deep high-level waste repository at Forsmark. From R-09-22 Figure 4-7.

2.2. Recommendations for detailed review

2.2.1. Review topics

What is the physical meaning of the Q-equivalent concept and how is it related to parameters that are calculated directly from hydrogeological models?

What is a valid Q-equivalent model for the case of spalling in deposition holes?

What is the importance of macrodispersion for far-field transport via DFN and ECPM blocks?

2.2.2. Analysis topics

What are consequences of potential changes to DFN and flow system during future glacial loadings?

What are consequences of alternative parametrizations of HCDs vs. depth?

Where does clay from the buffer go after it is eroded (does it clog fractures or does it remain in colloidal state until it has been removed far from the vicinity)?

3. Minor comments

3.1. Quality of report presentation

The main report (SKB TR-11-01) is generally clearly written and illustrated, and has been edited to a high standard. Very few grammatical or spelling mistakes were encountered during this review. Nomenclature in different sections of the report is in general consistent.

Methodologies are sometimes presented in too vague of terms, for example the description of groundwater flow modelling of the excavation and operation phase (TR 11-01, p. 298), for the reader to understand what has been done without recourse to the detailed background reports.

The term “pessimistic” is frequently used in referring to events or processes which are considered to be of low probability, and which could have negative consequences for safety if they do occur. For example, on p. 602-603 of TR-11-01, the case of a glacial stillstand without permafrost is referred to as “pessimistic.” This choice of adjective suggests that such cases are not realistic, when really what is meant is that they have low probability on the order of 0.01, or an expected low frequency of occurrence, over the duration of the next glacial cycle. Low-probability cases might still be realistic, and might not bound the range of possibilities that are realistic. The intended specific meaning of “pessimistic” as compared with “conservative” assumptions should be clarified.

The climate report section on ice sheet hydrology (TR-10-49, Section 3.2) is written at a pedantic and mostly schematic, qualitative level. While this type of presentation may be useful for conveying related aspects of the safety case to a general audience, the lack of quantitative presentation is a weakness for presentation of the safety case.

The geosphere processes report (TR-10-48) sections on hydraulic processes are written from a provincial viewpoint, entirely based on SKB's research to the exclusion of similar work in similar hydrogeological settings in Finland and Canada. Mention is made of “dolerite dykes at Laxemar” (p. 43) without any reference to a report that describes SKB's hydrogeological investigations of these features at the Laxemar candidate site.

The summary report on groundwater flow modelling methodology, set up and results (R-09-22) gives a very useful and clearly written overview of the three main groundwater modelling studies (R-09-19, R-09-20, and R-09-21), and how these are interrelated. The authors give good discussions of modelling assumptions that contribute to arguments of conservatism (for example on p. 106). There is however a tendency to overlook assumptions that might not be conservative; examples of possible non-conservative assumptions are discussed elsewhere in this review.

The background reports on groundwater modelling studies (R-09-19, R-09-20, and R-09-21) make very good use of visualizations to present the models and major results. Unfortunately, many of these figures do not include a length scale or coordinates to give a frame of reference (for example, Figure 3-1 in R-09-20, p. 28).

Plots of F use the same rainbow colour scheme (blue-green-yellow-orange-red for low to high values) as plots of near-field flows, but implications for safety are opposite. Note also that this colour scheme is unreadable for approximately 10% of the world population who suffer from red-green colour blindness; alternative colour scales have been suggested by the American Geophysical Union among others.

3.2. Engineered barriers

The role of tunnel plugs is discussed in TR 11-01 (p. 240). The plugs will eventually degrade; this is planned for in the design and appears to be handled consistently in the hydrogeological modelling.

The tightness of tunnel plugs may be an uncertainty for buffer erosion. According to TR 11-01 (p 306) a case in which 20% of the total volume of the tunnel leaks out through the plug is considered as an illustration. This amount appears to be arbitrary; it is unclear whether or how leakage through tunnel plugs will be measured to check this assumption. Sensitivity of the buffer erosion model to the assumed rate of leakage might be an issue to for further review.

A spalling depth of up to 5 cm is expected in 100 to 200 holes (TR 11-01, p. 294). The design calls for removal of spalled rock from the deposition holes, by scaling, when spalling is observed. However, it is not clear how removal of all spalled rock will be ensured prior to emplacement of canisters and buffer. Cases in which partially spalled rock is not detected, or is not successfully removed, do not appear to have been analyzed. How is spalling handled in matrix diffusion? A model for transport including matrix diffusion in a spalled zone is presented by Neretnieks et al. (2010); how this was applied within SR-Site has not been evaluated in this review but may be a topic for further evaluation.

The SR-Site Main Report suggests (TR-11-01, p. 668) that erosion of buffer will lead to decreased groundwater flow in the nearby fracture network, if the eroded buffer material remains near the deposition hole from which it was eroded. It is not clear that this supposition is motivated by either models or observations of the buffer erosion processes. An alternative and less optimistic possibility is that flow through the fracture network could increase due to opening of connecting pathways via deposition holes where buffer erosion has taken place.

3.3. Boundary conditions and initial conditions

Initial salinities in both matrix pore water and fracture water, for the groundwater flow simulations starting at 8000 BC, are based on mimicking present-day depth trends in matrix porewater salinity (TR 11-01, p. 293). Thus the initial condition is one of equilibrium between matrix and fracture porewaters, at 8000 BC. This is argued by SKB to be adequate to produce the observed differences between matrix and fracture porewaters.. A possible question for further review is whether this has any consequences for the calibration of mass-transfer parameters that govern exchange between matrix and fracture porewaters and

If the SFR is closed (TR 11-01, p. 299) and no longer pumped, this may also affect inflows to and time for resaturation of the deep repository. Early closure of the SFR

is discussed (TR 11-01, p. 314) in terms of effects on hydrogeochemistry, but not in terms of influence on inflows and resaturation for the deep repository.

Sea level rise could conceivably occur during the operating phase of the deep repository (TR 11-01, p. 310) due to the effects of global climate change. Considering that the surface facilities for the deep repository are located close to present-day sea level (particularly the northernmost ventilation shaft opening), the possible consequences and contingency plans for repository operation should be discussed.

The overall reasoning regarding oxygen penetration for buffer advection cases (TR 11-01, p. 605), including credit which is taken for stochastic effects, seems optimistic.. Oscillations in boundary conditions could conceivably have negative effects as well as positive effects for this issue.

4. References

[Other than primary review documents as listed in Appendix 1 which are referred to by number].

Berkowitz, B., Nauman, C., and Smith, L., 1994. Mass transfer at fracture intersections: An evaluation of mixing models. *Water Resources Research*, v. 30, p. 1765-1773.

Follin, S., 2008. Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-95, Svensk Kärnbränslehantering AB.

Geier, J., 2011. Investigation of discrete-fracture network conceptual model uncertainty at Forsmark. SSM Research Report 2011:13.

Long, J.C.S., Remer, J.S., Wilson, C.R., and Witherspoon, P.A., 1982. Porous media equivalents for networks of discontinuous fractures, *Water Resources Research*, Vol. 18, No. 3, P. 645. doi:10.1029/WR018i003p00645.

Munier R, 2010. Full perimeter intersection criteria. Definitions and implementations in SR-Site. SKB TR-10-21, Svensk Kärnbränslehantering AB.

Neretnieks, I., Liu, L., Moreno, L. 2010. Mass transfer between waste canister and water seeping in rock fractures. Revisiting the Q-equivalent model. SKB TR-10-42. Svensk Kärnbränslehantering AB.

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Painter, S, 2006. Effect of single-fracture aperture variability on field-scale transport. SKB R-06-25, Svensk Kärnbränslehantering AB.

Stephens M B, Fox A, La Pointe P, Simeonov A, Isaksson H, Hermanson J, Öhman J, 2007. Geology Forsmark. Site descriptive modelling Forsmark stage 2.2. SKB R-07-45, Svensk Kärnbränslehantering AB.

Tsang, Y.W., Tsang, C. F., Hale, F.V., and Dverstorp, B., 1996. Tracer transport in a stochastic continuum model of fractured media. *Water Resources Research*, Vol. 32, No. 10, p. 3077, doi:10.1029/96WR01397.

Coverage of SKB reports

Table A1.1: List of reports considered in this review, and degree of coverage for each report.

Reviewed report	Reviewed sections	Comments
TR-11-01 Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site Project	4.1-4.4, 4.6-4.9, 7.4.5, 8.3.4, 8.4.5, 10.1.3, 10.2.3, 10.3.6, 10.4.6, 13.4, 14.4.6, 15.5.13-14, 15.6.2-5	Primary review.
	4.5, 4.10.1, 5.2.3,	Read for background understanding.
TR-10-48 Geosphere process report	3.1, 5.2, 6.1	Primary review.
TR-10-52 Data report	6.3, 6.6, 6.7	Primary review.
TR-10-49 Climate report	3.2	Primary review.
R-09-19 Groundwater flow modelling of the excavation and operational phases – Forsmark	All	Read for background understanding, not detailed review.
R-09-20 Groundwater flow modelling of periods with temperate climate conditions – Forsmark	All (but only cursory review of appendices)	Appendices C & F are of interest for hydrogeochemical review; Appendices D, E & G (definition and results of performance measures) are of interest for radionuclide migration and integrated safety assessment review.
R-09-21 Groundwater flow modelling of periglacial and glacial climate conditions - Forsmark	All	Read for background understanding, not detailed review.
R-09-22 SR-Site groundwater flow modelling methodology, setup and results	All	Reviewed as summary of the main results of the three preceding reports.

Suggested needs for complementary information from SKB

1. Request goodness-of-fit statistics for the ECPM tensors computed by ConnectFlow for Forsmark.
2. Request ECPM tensor data passed from ConnectFlow to DarcyTools.
3. Request pressure & density data passed from regional-scale model to site-scale model
4. What happens to particles that do not discharge from the surface boundary of the flow models? How are they accounted for?
5. What are SKB's reasons for choosing the aperture-transmissivity models that are utilized and not considering a broader range, such as the bounding case of the cubic law? Have aperture-transmissivity correlations with a stochastic component been considered and/or ruled out as cases of interest?
6. How are flow path widths and flow segment lengths defined in DFN particle tracking results from ConnectFlow?
7. What are SKB's plans for demonstrating methods for verifying achievement of the design premises in the repository?
8. What is the effect of no-flow boundary conditions on inflows to repository & SFR? (See Figure 2.1).
9. Should the extended spatial variability case be propagated throughout the safety assessment, as it appears to be more realistic and produces shorter discharge paths and lower F values in the late temperate period.
10. What is the importance of lower resolution of the structural model in offshore areas; are there no variants to test this?

Suggested review topics for SSM

1. What is the physical meaning of the Q-equivalent concept and how is it related to parameters that are calculated directly from hydrogeological models?
2. What is a valid Q-equivalent model for the case of spalling in deposition holes?
3. What is the importance of macrodispersion for far-field transport via DFN and ECPM blocks?
4. What are consequences of potential changes to DFN and flow system during future glacial loadings?
5. What are consequences of alternative parametrizations of HCDs vs. depth?
6. Where does clay from the buffer go after it is eroded (does it clog fractures or does it remain in colloidal state until it has been removed far from the vicinity)?



2012:41

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

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

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

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