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Technical Note

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Review of Groundwater Chemistry in SKB's Safety Assessment SR-Site

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SSM perspektiv

Bakgrund

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

Projektets syfte

Syftet med detta projekt är att granska SKB's hantering av den långsiktiga utvecklingen av grundvattenkemi som inkluderar perioder med olika klimat som tempererade betingelser, permafrost och glaciala betingelser. Den nu avslutade karakteriseringen av grundvattenkemi vid Forsmark utgör en grund för förståelse av den geokemiska och hydrologiska utvecklingen under långa tidsperioder. Geokemiska processer (och även mikrobiologiska) i närområdet av ett slutförvar som påverkar redox och pH har en särskild betydelse eftersom redox och pH tillståndet påverkar kopparkapselns korrosionsmekanismer och även förutsättningarna för retardation och transport av radionuklider (för grundvatten som kommer i kontakt med kopparkapslar och bränsleelement).

Författarnas sammanfattning

Denna inledande granskning undersökte SKB:s karakterisering av grundvattenkemi vid Forsmark samt den långsiktiga utvecklingen av grundvattenkemi under långa tidsperioder och för olika möjliga framtida klimattillstånd. Denna granskning undersökte om de geokemiska data som SKB tagit fram är rimliga och tillräckliga och om metoderna som SKB har använt för att förutsäga geokemiska betingelser i framtiden är lämpliga. Granskningen har baserats på information som tillhandahållits av SKB i huvudrapporten för SR-Site projektet samt i olika understödjande referenser till huvudrapporten.

På ett generellt plan förefaller SKB:s insamling och tolkning av grundvattenkemi data från undersökningen av Forsmarksplatsen vara tillräckligt bra. SKB har till exempel identifierat sulfidkoncentrationer som en viktig men osäker del av en säkerhetsfunktion och har därför på ett lämpligt sätt tillhandahållit ytterligare resurser för kontroll och förbättring av användbarheten av insamlad data. SKB har trots svårigheterna med att samla in representativa grundvattenprover lyckats i kandidatområdet få tag i ett flertal grundvattenprover med skälig kvalitet.

Det finns dock särskilda regioner i kandidatområdets bergvolym där det finns få eller inga grundvattenkemidata av hög kvalitet. En ytterligare insats bör göras för att komplettera tillgängliga data med nya data från dessa regioner. Granskarna hade dessutom vissa problem med att spåra slutsatserna baserade på data till deras ursprungliga källor. Inom denna granskning fastställdes att SKB:s modellering för att beskriva utvecklingen av grundvattenkemiska är rimlig, även om modellen inte fullt ut kunnat verifieras genom jämförelser med kemiska analyser och fältobservationer. Granskningen har också identifierat möjliga osäkerheter kopplade till hur karakteriserings- och konstruktionsaktiviteter bidrar till lokal mikrobiell bildning av sulfider.

SKB använder grundvattenkemidata primärt som indata för konceptuella modeller och för att ta fram sammansättningen av referensgrundvattentyper för modelleringen av utvecklingen av grundvattenkemi under framtida klimattillstånd. SKB använder flera olika grundvattenflödesmodeller, som var och en har olika möjligheter och begränsningar för att simulera rörelser och blandning av grundvatten i olika flödesvägar i berget under olika klimattillstånd. SKB använder för ett antal geokemiskt relevanta säkerhetsindikatorer, blandningsproportioner från flödesmodeller och lät blandningarna komma i jämvikt med en uppsättning reaktiva mineral för att uppskatta sammansättningen av grundvatten under tempererade och glaciala betingelser. SKB använde de geokemiska modelleringsresultaten för att ta fram en användbar uppsättning av tidsberoende och tredimensionella återgivningar av grundvattenkemi för förvarsvolymen och dess omgivning. Detta modelleringsarbete medförde också en stor uppsättning utdata som SKB har använt för att ta fram statistiska fördelningar av koncentrationer för geokemiska komponenter inom förvarsvolymen.

Syftet har varit att få insikter om geokemiska säkerhetsfunktioner. All utdata inklusive variabilitet för framtida grundvattensammansättningar är dock i sista hand härledd från SKB:s val av sammansättning för de referensgrundvattentyper som används i blandnings- och jämviktsberäkningar. Den referensgrundvattentyp som representerar det salta djupa grundvattnet är särskilt viktig eftersom det är en av endast två referensgrundvattentyper som använts vid modellering av den glaciala cykeln. Det finns dock inga faktiska mätningar av denna grundvattentyp trots att statistiska analyser och undersökningar vid Laxemarplatsen liksom andra platser i Skandinavien visar att den grundvattentyp med hög salthalt borde finnas vid Forsmark. Avsaknaden av bekräftelse av existensen av den djupa salta referensgrundvattentypen vid Forsmark kan ha en inverkan på den förväntade salthaltsutvecklingen på förvarsdjup under en glacial cykel, och detta skulle kunna motivera en modifiering av den initiala hydrokemiska konceptuella modellen.

Under denna initiala gransking identifierades flera frågor för vilka det erfordras klargörande information från SKB. Strålsäkerhetsmyndigheten (SSM) kan också behöva göra ett antal oberoende utvärderingar under huvudgranskningsfasen för att öka tilltron till slutsatserna från myndighetsgranskningen. Spårbarheten från undersökningar syftande till att ta fram data till deras tillämpning i förhållande till säkerhetsfunktioner för utvecklingen av SKB:s säkerhetsanalys är till exempel inte alltid transparent, vilket delvis beror på den stora datavolym som har samlats in på platsen under årens lopp.

Granskarna rekommenderar också kompletterande information eller en mera detaljerad granskning för att verifiera att SKB:s uteslutande av jonbytesprocesser från utfört modelleringsarbete inte har någon betydelsefull effekt på utvärderingen av säkerhetsfunktioner relaterade till grundvattnets jonstyrka eller eventuellt förhöjda koncentrationer av potentiellt skadliga lösta grundvattenspecier. Det bör också påpekas att den uppskattade framtida variabiliteten för grundvattenkemi liksom statistiska förhållanden mellan modellerade utdata är till nästan uteslutande härledd från antaganden kring sammansättningen av de fem referensgrundvattentyper samt från blandningsförhållanden som genererats från de platsspecifika hydrogeologiska modellerna.

Som ett resultat av detta är SKB:s slutsatser och uppskattade osäkerheter kring framtida geokemiska betingelser på ett påfallande sätt kopplat till antaganden och osäkerheter för grundvattenflödesmodellerna. Den mera detaljerade huvudgranskningsfasen bör därför inkludera en noggrann utvärdering av integrationen av osäkerheter mellan hydrogeologiska och geokemiska modeller.

Projektinformation
Kontaktperson på SSM: Bo Strömberg
Diarienummer ramavtal: SSM2011-3639
Diarienummer avrop: SSM2011-4260
Aktivitetsnummer: 3030007-4013

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 this project is to review of SKB's treatment of long-term groundwater chemistry development including various periods of different climate such as temperate, permafrost and glacial conditions. The completed groundwater chemistry characterization at the Forsmark site provides an important basis for understanding the site geochemical and hydrological development during long-time periods. The near-field geochemical (and microbial) processes affecting redox and pH conditions of groundwater have a particular importance, since the redox and pH state affect various canister corrosion mechanisms as well as conditions for radionuclide retardation and transport (groundwater contacting e.g. copper canisters and spent fuel elements).

Summary by the authors

This initial review examined SKB's characterization of groundwater chemistry at the Forsmark site and its evolution during long time periods under different possible climates in the future. The review considered whether the geochemical data provided by SKB are reasonable and sufficient and whether the methods used by SKB for projecting geochemical conditions into the future are appropriate. The review is based on information provided by SKB in the main report of the SR-Site project and in various main and supporting references for the safety report.

Overall, SKB's acquisition and interpretation of groundwater chemistry data as part of the Forsmark site characterization appear to be adequate. For example, SKB identified sulphide concentrations as an important but uncertain contributor to a safety function and appropriately dedicated additional effort to screening and improving the usefulness of the collected data. Despite the difficulty of collecting representative groundwater samples under low flow conditions at depth, SKB has obtained numerous water samples of at least reasonable quality throughout the candidate site area. However, there are particular regions of the candidate repository volume that have little or no high quality hydrochemical data, and an effort should be made to supplement the available data with new data from those regions. Also, the reviewers had some difficulty tracing data-based conclusions to their original source.

The review determined that the SKB modelling to describe the evolution of groundwater chemistry is reasonable though the model has not been fully verified by comparison with chemical analyses and field observations. The review has also identified potential uncertainties about the contribution of site characterization and construction activities to localized microbial production of sulphides.

SKB used the groundwater chemistry data primarily as input to conceptual models and to develop reference end-member water compositions for modelling the evolution of groundwater chemistry under future climate conditions. SKB used several different groundwater flow models, each with its own capabilities and limitations, to simulate the movement and mixing of waters along flow paths during different climate states. For a number of the geochemically significant safety indicators, SKB used groundwater mixing proportions from the flow models and equilibrated the mixtures with a set of reactive mineral phases to estimate the composition of groundwater under temperate and glacial cycle conditions. SKB used the geochemical modelling results to generate a useful set of time-dependent and three-dimensional depictions of groundwater chemistry across the site.

The modelling also provided a large set of output data that SKB used to estimate the statistical distribution of geochemical components within the repository horizon to provide insights about geochemical safety functions. However, all of the modelled output, including the variability in future groundwater compositions, ultimately is derived from SKB's choices for the starting end-member water compositions that were used in the mixing and equilibration calculations. The deep saline end-member is particularly important because it is one of only two end-member compositions used in the glacial cycle modelling. However, although statistical analyses and studies at Laxemar and other Scandinavian sites suggest that a high-salinity end-member should be present at the Forsmark site, no such samples have been collected to date. The lack of confirmation of the presence of a deep-saline end member at Forsmark could have implications for the expected salinity evolution near the repository horizon during glacial cycles, and it could suggest that a modification of the initial site hydrochemical conceptual model is warranted.

The initial review identified several topics for which clarifying information from SKB should be requested. The SSM may also wish to conduct a few independent evaluations during the main review phase to gain confidence in its regulatory findings. For example, the traceability between the data-level investigations and their application to safety functions in the development of the SKB safety case is not always transparent, in part due to the large volume of information collected over the years at the site.

The reviewers also recommend complementary information or a more detailed review to verify SKB's assumption that omitting cation exchange processes from the modelling has no significant effect on the evaluation of safety functions related to ionic strength and elevated concentrations of potentially detrimental dissolved species. In addition, the projected future variability in groundwater chemistry and the statistical relationships within the modelled output are derived almost entirely from the starting assumptions about the compositions of the five end-member waters and from the mixing proportions that were generated by the site hydrogeological models.

As a result, SKB's conclusions and uncertainties about future geochemical conditions are conspicuously linked to the assumptions and uncertainties of the groundwater flow models. The more detailed main phase review accordingly should include a careful evaluation of the integration of uncertainties between the hydrogeological and geochemical models.

Project information

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Contents

1. Introduction

On 16 March 2011, the Swedish Radiation Safety Authority (SSM) received a license application from the Swedish Nuclear Fuel and Waste Management Company (SKB) for construction of a spent nuclear fuel repository to be located in Forsmark, Östhammar Municipality as well as to build an encapsulation facility for spent nuclear fuel in Oskarshamn. The safety assessment SR-Site, which was part of the submitted license application materials, is being reviewed by SSM in a stepwise and iterative fashion. The first step is called the Initial Review Phase. The overall goal of the Initial Review Phase is for SSM to achieve a broad coverage of the information provided in SR-Site and its supporting references and in particular to identify where complementary information or clarifications need to be delivered by SKB.

This technical note is part of a set of reviews for SSM by external experts to assist with the Initial Review Phase. The assignment involves a broad review of SKB's treatment of the characterization and evolution of groundwater chemistry, including various periods of different climate such as temperate, permafrost, and glacial conditions. The characterization of the existing groundwater chemistry at the Forsmark site provides an important basis for understanding the evolution of the site geochemistry and hydrogeology during long time periods. The near-field geochemical and related microbial processes affecting redox and pH conditions of groundwater have a particular importance because these conditions affect various canister corrosion mechanisms as well as conditions for radionuclide mobilization, retardation, and transport. In addition, a sound large-scale understanding of the coupled nature of hydrogeology and the site groundwater chemistry provides a basis for assessing the evolution of flow patterns near the repository over long time scales.

1.1. Objective

The objective of the initial review is to assess the clarity, comprehensiveness, and traceability of the groundwater chemistry information presented by SKB, and how SKB has used the information to support the site safety case. The initial review is focused on two main considerations. First, are the SKB data reasonable and sufficient to characterize the present-day geochemical conditions at the Forsmark site? Second, are the methods utilized by SKB sufficient to define the geochemical evolution of groundwater that will interact with the repository near-field environment over long time periods? The initial review process is designed to facilitate the main review process by identifying, in advance, parts of the SKB safety case where (i) omissions or gaps in required technical information are present, (ii) additional or clarifying information from SKB is needed, (iii) additional detailed analyses are needed, or (iv) a more detailed assessment is recommended during the main review phase.

1.2. Approach

This initial review of groundwater chemistry is structured in two parts: a broad evaluation of the geochemical site characterization data and its application in the development of a site paleohydrogeological model, and a broad evaluation of the methods used by SKB to estimate the evolving future composition of groundwater at the Forsmark site. The key SKB documents, or portions thereof, that were covered by the review are listed in Appendix 1. The reports include the main report of the SR-Site project (SKB, 2011), various main and additional SKB supporting references for SR-Site, and related reports about the development of the Forsmark site descriptive model. The reviewers also consulted journal papers and reports by other technical organizations that were cited by SKB in the above reports. Although these other sources were not formally part of SR-Site, they contributed to the reviewers' understanding of the background material.

2. SKB characterization of groundwater chemistry and related processes

Site hydrochemical data and conceptual models play important roles in many aspects of SKB's safety assessment of the Forsmark Site and the proposed repository. A primary safety function of the geosphere is to provide chemically favourable conditions for the proposed repository (SKB, 2011). The hydrochemical conditions identified by SKB as important to the safety performance of the repository system include (i) the presence of reducing conditions to limit canister corrosion, to lower solubilities of important radionuclides, and to provide redox conditions favourable for radionuclide sorption, (ii) the presence of salinities that are neither so high that they limit potential swelling in the backfill, nor so low that they promote the formation and stability of colloids, (iii) low concentrations of detrimental species such as sulphide, which could potentially enhance canister corrosion; (iv) low concentrations of naturally occurring colloids, which could enhance the transport of certain radionuclides, (v) a moderate range of pH values, which is desirable for a number of engineered barrier and radionuclide solubility and sorption issues, and (vi) no combination of low pH and elevated chloride values that could contribute to canister corrosion (SKB, 2011). SKB also used the measured concentrations of naturally occurring radionuclides in groundwater at the Forsmark site to evaluate alternative indicators of risk to support the SKB safety case. For example, SKB noted that the calculated repository-derived releases of the U-238 decay chain (including U-234 and Ra-226), which were important contributors to dose, were roughly two orders of magnitude less than the present-day naturally occurring fluxes of these radionuclides at the site (SKB, 2011, Section 13.5.8).

SKB collected water samples from the Forsmark site area and integrated sampling results with data and conceptual models from studies at Laxemar and Äspö (Salas et al., 2010; SKB, 2008). SKB implemented a comprehensive and integrated hydrochemical characterisation process that included sampling for a wide range of relevant chemical parameters including major ions, trace metals, stable and radiogenic isotopes, dissolved gases, organic and inorganic carbon, microbes, and colloids (Laaksoharju et al., 2008; SKB, 2008). Samples were collected from surface and near-surface waters and at a variety of groundwater depths using a combination of percussion and cored boreholes (SKB, 2008). SKB conducted a controlled sampling program called the complete chemical characterisation (CCC) to establish a baseline hydrochemical dataset from the cored boreholes and subsequently established and maintained a hydrochemical monitoring program to periodically collect samples from completed boreholes (SKB, 2008; Laaksoharju et al., 2008). Groundwater collected from the boreholes is thought to be representative of water flowing in fractures and deformation zones (SKB, 2008). Porewaters from bedrock were also extracted from cores to provide data for the low-transmissivity regions (SKB, 2008).

SKB has used the cumulative results of the hydrochemical sampling and characterisation program to develop a conceptual model for hydrochemistry at the Forsmark Site and to inform the development of the hydrologic models simulating groundwater flow at the site (SKB, 2011; Laaksoharju et al., 2008). SKB has interpreted and modelled the data to develop several candidate end-member water compositions, which were then used in mixing models to describe the hydrochemical evolution of the site over time (Salas et al., 2010; Laaksoharju et al., 2008), as described in Section 3 of this technical note.

To assess the clarity, comprehensiveness, and traceability of the hydrochemical information used to support the repository safety case, the reviewers conducted a comparison of hydrochemical conceptual models and model output with the data used to build those models and evaluated the traceability of model inputs to original data. For example, hydrochemical data used to construct descriptive plots of parameter concentration variations with depth (SKB, 2011, Figure 10-38) were traced back to the original modelling report (Salas et al., 2010) and to the originating data reports for particular boreholes (Berg and Nilsson, 2008). Results of the review are discussed in Section 4.

3. SKB models for past and future evolution of groundwater chemistry

During site characterization activities at the Forsmark site, SKB developed a conceptual model that described the past evolution of the system, including pervasive large-scale changes in groundwater chemistry related to past glaciations (Laaksoharju et al., 2008, Sections 2.3, 2.4, and 2.5). The hydrogeochemical evolution model is based on chemistry and isotope data obtained from groundwater and matrix porewater samples during the site characterization activities. SKB developed the present-day hydrogeochemical conceptual model in the context of the spatial distribution of the analyzed groundwater compositions in relation to rock domains, fracture domains, and deformation zones. The model includes a component that SKB describes as “ancient” meteoric water with a warm-climate isotopic signature that preceded the last glaciation. The characteristics of this water chemistry are detected in certain matrix porewater samples and as a mixing component in other groundwaters. SKB identified five distinct groundwater types in the present-day system: saline water, brackish non-marine water, meltwater from the last deglaciation, brackish marine water (Littorina/Baltic seawater), and fresh water (derived from present-day meteoric recharge). SKB used a statistical approach, Principal Component Analysis, to determine representative chemical compositions for the original end-members for these groundwater types (Laaksoharju et al., 2008, Table 1-1) for use in geochemistry modelling.

SKB also used groundwater chemistry data to develop and test hydrogeological models. Simulations of groundwater flow for the temperate climate period (Joyce et al., 2010, Section 6.2) included the mixing of the five defined reference water compositions over the equivalent of the period from 8,000 BC to 12,000 AD. Simulations for groundwater flow modelling for time periods with periglacial and glacial climate conditions (Vidstrand et al., 2010) used groundwater salinity data to model mixing relations between a saline groundwater and a dilute groundwater, with additional dilution provided where required by a third end-member, glacial meltwater (Salas et al., 2010, Section 3.1).

SKB evaluated future changes in groundwater chemistry for three distinct time periods, using different methods for the estimates in each case. For the short-term excavation and operational period, spanning approximately 100 years, SKB explicitly considered changes that would be related to drawdown and upwelling in the vicinity of the repository openings, as well as near-field solid-water interactions resulting from exposure of groundwater to repository materials and the effects of ventilation. The predicted short-term changes in groundwater chemistry included a potential increase in salinity from upconing of deeper waters; the introduction of atmospheric oxygen from ventilation in the repository and from oxygenated water; increased alkalinity and elevated pH due to reactions with grout, shotcrete, and concrete; and increases in dissolved organics and microbial activity (SKB, 2011, Section 10.2.5). SKB based the description of short-term effects on site characterization information, data from experiments, and reasoned arguments. From the information considered, SKB concluded that none of these processes would result in significant changes in water chemistry that would affect long-term safety functions of the repository. SKB also identified that some more persistent changes to near-field water chemistry are expected to result from longer-term interactions with concrete, grout, bentonite, and other engineering materials (Sena et al., 2010), but those aspects of the SKB safety case are outside the scope of this initial review.

To model how the Forsmark site groundwater chemistry is expected to evolve under temperate climate conditions over approximately the next 10,000 years, SKB obtained the calculated groundwater mixing proportions at tens of thousands of points from the site groundwater flow models (Joyce et al., 2010). SKB then used the geochemical modelling software PHREEQC to mix the end-member waters in the proportions specified by the flow models at each point and to react the resulting mixture with a set of specified minerals (Salas et al., 2010) to achieve chemical equilibrium with those phases. The modelling approach provided a detailed three-dimensional, time-varying perspective of the geochemical evolution of the site during a temperate climate period.

SKB adopted a similar modelling approach to estimate the evolution of groundwater chemistry during periglacial and glacial conditions that would be part of a long-term glacial cycle spanning conditions of approximately 100,000 years. However, in contrast to the SKB modelling for the temperate climate, the SKB groundwater flow modelling for glacial conditions did not use mixing proportions among five end-member water compositions.

Instead, the hydrogeological model provided only salinity values based on mixing a saline groundwater and a diluted groundwater (Salas et al., 2010). Later climate stages in the flow model added a third mixing component to represent further dilution of the groundwater by glacial meltwater (Vidstrand et al., 2010). Separate flow models were developed to represent various stages of glacial cycles, including a submerged saline period, infiltration of glacial meltwaters, upconing of deep saline waters associated with the advance of an ice sheet, and the effects of a frozen soil underneath an ice sheet. After establishing mixing proportions, SKB again used the geochemical modelling software PHREEQC to mix the end-member waters in the specified proportions and to react the mixture with a set of specified minerals (Salas et al., 2010).

SKB used the results of the temperate and glacial cycle hydrogeochemical evolution models to inform various aspects of the SR-Site safety assessment, with a particular focus on the geosphere-related safety functions pertaining to chemically favourable conditions for a reducing environment, salinity, ionic strength, limited concentrations of certain minor elements, pH levels, and chloride concentration (SKB, 2011, Section 8.3.4). SKB also relied directly on site characterization data, on reasoned arguments, and on additional modelling to assess the expected variation of several geochemical characteristics that were either not addressed by the geochemical modelling efforts or that were associated with significant uncertainty (e.g., SKB, 2010a; Sidborn et al., 2010; Tullborg et al., 2010).

4. Discussion and recommendations

The focus of this initial review was on determining whether the methods utilized by SKB to define the near-field water chemistry are appropriate and sufficient for the purpose, and whether the range of geochemical conditions defined by SKB's field sampling and geochemical modelling appear to be reasonable and defensible enough to proceed with a more detailed technical review in SSM's Main Review Phase. During the review, areas were identified where additional information will facilitate detailed SSM review; these suggested requests for complementary information are listed separately in Appendix 2. Clear links between the requested complementary information and the safety case are provided to establish the need.

A discussion of the initial review findings is provided for two main topic areas: (i) SKB's acquisition and interpretation of groundwater chemistry data with respect to the development of a safety case, and (ii) SKB's methods to address the variation of groundwater chemistry over time for the repository setting. In addition to noting key areas in which the initial review finds that SKB's presentation of information appears to be sufficient, the review also identifies several potential uncertainties or issues important to safety that will require a more focused assessment during the main review phase. In some cases, the detailed review could be supported by independent modelling calculations to evaluate the basis of specific SKB safety-related conclusions. The suggested review topics to be considered in more detail during the main review phase are summarized in Appendix 3.

4.1. Acquisition and interpretation of groundwater chemistry data

SKB's hydrochemical characterisation of the Forsmark Site appears to be reasonably complete. The difficulties of collecting representative groundwater samples under low flow conditions at depth are well known, yet SKB's sampling program and detailed uncertainty and data evaluation process enabled the collection of numerous samples of reasonable quality throughout the candidate site area (e.g., Nilsson et al., 2010; Laaksoharju et al., 2008; Berg and Nilsson, 2008; Auque et al., 2008; Berg et al., 2006). Given the difficulties of sampling from deep boreholes, it is not surprising that only a limited number of better quality data (SKB's Category 1-3) have been collected and are available (Laaksoharju et al., 2008). Hydrochemical data were used primarily as input to conceptual models and detailed interpretations. SKB provided support for reasoned arguments in developing the site hydrochemical conceptual model and reference end-member water compositions (Salas et al., 2010; Laaksoharju et al., 2008; SKB, 2008). The end-member water compositions are important in that they form the basis for the detailed modelling used to examine future hydrochemical evolution of the site (Salas et al., 2010).

The deep saline end-member is particularly important because it is one of two compositions used in the glacial cycle modelling (Salas et al., 2010). While statistical analyses and studies at Laxemar and other Scandinavian sites suggest that a high-salinity end-member should be present at the Forsmark site (Salas et al., 2010; Laaksoharju et al., 2008), no such samples have been collected to date (SKB, 2008). The lack of confirmation of the presence of a deep-saline end-member at Forsmark could have implications for the expected salinity evolution near the repository horizon during glacial cycles, or it could suggest that a modification of the initial site hydrochemical conceptual model is warranted. Additionally, based on review of the figures and information presented in the site description and main report for the SR-Site project (SKB, 2011; 2008), there are particular regions of the candidate repository volume that appear to have little or no high quality hydrochemical data. The particular regions include the target area/volume at depths below 500 m. Given the current arrangement of boreholes and sampling locations at Forsmark (SKB, 2008), it seems unlikely that additional samples from these same boreholes will bridge the data gap. An effort should be made to supplement the available data with new data from those depths. This would be of use in reducing the uncertainty in locating the transition from brackish non-marine to deeper saline waters near and under the proposed repository horizon (e.g., SKB, 2008, Figure 9-22). Clear identification of the brackish to deep saline (or deep old meteoric) transition zone will improve confidence in predictive models of salinity changes near the proposed repository horizon and may help to identify areas in which microbes may be most active. As recommended in Appendices 2 and 3, SSM should request that SKB provide additional data to support the presence of the deep-saline end-member or describe the impacts of the presence of deep waters that have lower or higher salinity than has been assumed. Also, SSM may choose to conduct an independent evaluation of the effects that different or unexpected water salinities at depth would have on the prediction of salinity transients near the repository horizon.

Site hydrochemical data are also used to compare predicted mixing model output to current conditions within the candidate repository volume (SKB, 2011; Salas et al., 2010). The comparisons are useful but tend to highlight the failure of the mixing models to reproduce some of the hydrochemical trends observed in the collected samples from the Forsmark Site. Examples are seen in Figures 6-5 and 6-9 of Salas et al. (2010), where the model-predicted calcium and phosphate concentration trends with depth do not reproduce the measured trends. Also, Figure 6-10 of Salas et al. (2010) shows that modelled pH follows a distinctly lower trend with depth than is indicated by many of the measured values. SKB acknowledges that the uncertainties may be a result of model simplifications, such as assuming the modelled waters are in equilibrium with specified mineral phases, or not including ion-exchange processes in the geochemical model (SKB, 2011; Salas et al., 2010). However, SKB does not otherwise address the potential significance of using a modelling approach that is not clearly validated by site data, even for present-day conditions, to represent the evolution of groundwater chemistry over long time periods in the future. Recommendations for more detailed review and potential supporting analyses to examine alternative conceptual models are provided in Appendices 2 and 3.

Where additional detailed data scrutiny and analysis have been recognized to be warranted, SKB has initiated and conducted the analyses. This is exemplified by Tullborg et al. (2010). SKB identified sulphide concentrations as an important but uncertain contributor to a safety function and (appropriately) dedicated additional effort to screening and improving the usefulness of the collected data. Tullborg et al. (2010) also provides an excellent example of clear, transparent, and traceable assembly and use of field-collected hydrochemical data. Data sources and evaluations are discussed and the data used are clearly presented within the report (Tullborg et al., 2010). This is in contrast to data used in other reports (e.g., Salas et al., 2010; Laaksoharju et al., 2008; SKB, 2008). One example of a potential data traceability issue is seen in Figure 10-38 of SKB (2011). This figure reproduces Figure 6-5 of Salas et al. (2010) and provides a similar conclusion. However, the number of Category 1-3 data points shown in the SKB (2011) figure is greater than shown in the Salas report although the same source is referenced. It appears that additional data were used to make Figure 10-38 of SKB (2011), but the source of the data is not known and a search of other reports for the available data was not successful in locating the source of the new data (e.g., Nilsson et al., 2010; Berg and Nilsson, 2008). This highlights the need for SSM to critically review and trace the accuracy of data used to support hydrochemistry conditions important to safety.

The review of sampling procedures (e.g., Berg et al., 2006) and results of the detailed analyses of sulphide concentrations at the site (Tullborg et al., 2010) indicate that perturbations of the natural hydrochemical system often result in increased sulphide concentrations, likely as a result of increased activity of sulphate-reducing bacteria

(Tullborg et al., 2010). Site data collected on microbial activity suggest that transition zones between hydrochemical boundaries may feature increased microbial activity (SKB, 2008). SKB does not evaluate the potential for site construction and subsequent waste emplacement activities to produce a sulphide bloom similar to that which SKB has observed in the deep monitoring boreholes. This increase in activity may be independent of the added carbon content and may be a result of hydrochemical system disturbance only. SSM should request additional information from SKB to analyse the potential for and possible persistence of a sulphide bloom at the repository horizon. This information might include an evaluation of the potential of the repository and associated disturbed horizon to act as an accumulation zone for sulphide (similar to the smaller scale accumulation observed in the boreholes). Studies of microbial activity in the deep subsurface indicate that stratigraphic and hydrochemical transition zones are often regions of enhanced microbial activity (Krumholz, 2000). Construction of the repository creates a physical transition zone in addition to the nearby but relatively undefined brackish-saline transition. A sensitivity analyses of the accumulated effects of the combination potentially detrimental features (sulphide accumulation, zone of microbial activity) may be warranted.

The SKB paleohydrology model, which described multiple large-scale changes in groundwater chemistry over a depth of hundreds of meters in response to glaciation and related effects, served as a conceptual model for SKB's geochemical modelling of future conditions. SKB modelled expected changes in chemistry by mixing groundwaters and then equilibrating them with specified common or anticipated low-temperature mineral phases (Salas et al., 2010). For example, the modelling approach assumed that if a given mixture were undersaturated with respect to calcite, sufficient calcite would be present, in the rock matrix or as a fracture-lining mineral, to dissolve until the water achieved equilibrium; alternatively, if the given mixture were oversaturated, then calcite would precipitate from the groundwater as necessary. To some extent, the validity of the geochemical modelling assumptions can be tested by examining the evidence for low-temperature mineral precipitation and dissolution reactions in existing fractures at the Forsmark site. However, it is not clear, based on the initial review, whether the sparse and thin late-stage fracture mineral coatings described by SKB (e.g., Sandström et al., 2008) support the assumption that previous large-scale changes in groundwater chemistry should have resulted in widespread or texturally varied (i.e., a combination of dissolution and growth phases) late-stage fracture mineralization. Complementary information and supporting analyses about the relative importance of precipitation and dissolution of late-stage minerals such as calcite, as recommended in Appendices 2 and 3, would assist SSM to conduct a more detailed review of the validity of SKB's geochemical model and the consideration of alternative conceptual models in this respect.

SKB notes that "a full propagation of uncertainties, from the hydrogeological modelling into the geochemical calculations, has not been performed" (SKB, 2011, p.357). SSM should request that SKB evaluate the impact of cumulative uncertainties on the hydrochemical model predictions. These analyses could help to explain the predictions of chemical parameters that often fall outside the range of the end-member composition envelope (e.g., Salas et al., 2010, Figure 6-14).

4.2. Methods to describe the variation of groundwater chemistry over time

Overall, SKB has used site characterization data effectively to inform models about how groundwater chemistry is likely to change under specific future conditions. The SKB description of the evolution of groundwater chemistry at the Forsmark site is based on a reasonable present-day conceptual model that uses an extensive data set of geochemical and isotopic analyses acquired by SKB during several stages of site characterization activities. The present-day conceptual model integrates the site geology and structure, major groundwater flow paths, and variation of groundwater chemistry with depth and in relation to key structural features and groundwater flow paths, including the shallow-dipping deformation zones ZFMA2 and ZFMF1 (SKB, 2008, Section 11.3.3).

SKB applied a widely used statistical analysis technique, principal component analysis, to the large geochemical and isotope data set and interpreted the results to identify five distinct end-member groundwater compositions at the Forsmark site. SKB used the representative water compositions to develop a paleohydrology model for the evolution of groundwater chemistry during the most recent previous glacial cycle. SKB then used insights from the paleohydrology model to identify potential stages in future climate evolution that would be likely to have significant effects on groundwater chemistry. SKB used several different groundwater flow models, each with its own capabilities and limitations, to simulate the rate, direction, and mixing of waters along groundwater flow paths during different climate states. In particular, SKB made comprehensive use of site data in the geochemical modelling of temperate climate conditions, in which the modelling input files were directly associated with flow model output files that were based on mixtures of the five distinct end-member water compositions. This technical note has not assessed the validity or acceptability of SKB's groundwater flow models, but it should be noted with caution that SKB's modelling of the geochemical evolution of the system over time is closely linked to the assumptions and appropriate use of the hydrogeological models because the output of the flow models is used directly as input for the PHREEQC geochemical mixing and equilibration calculations. Accordingly, the main review phase should carefully examine the integration of the hydrogeological models and the geochemical modelling, with a particular focus on SKB's treatment of uncertainty between the flow models and the related assumptions of the geochemical evolution models.

By linking the geochemical modelling calculations to the thousands of modelled points in the hydrogeological flow models, SKB generated a set of three-dimensional visualizations of site-wide spatial and temporal changes in water chemistry that depict the evolution of the system over long time periods. SKB also used the detailed output of the PHREEQC modelling to generate other useful graphic representations of the data, such as vertical and horizontal slices of the three-dimensional modelling, box-and-whisker plots showing the statistical distribution of certain components within the repository horizon, and comparisons of modelled and measured distributions of certain components at different depths (Salas et al., 2010). SKB's use of these figures was effective in conveying the results of the modelling concisely and clearly.

SKB's integration of site characterization data and modelling approaches to describe how groundwater chemistry is likely to change under specific future conditions was best constrained for temperate climate conditions. The input for the PHREEQC modelling was closely tied to the SKB groundwater flow model that had been developed using the five representative end-member groundwater compositions (which, in turn, were developed from geochemical site characterization data). The conceptual uncertainties in the modelling for glacial cycle conditions are larger, and the geochemical calibration of the glacial cycle hydrogeological models is less robust, because the glacial cycle modelling relied on two generalized groundwater types, a saline water and a dilute water, and relied only on one measured parameter, salinity values, to constrain the flow model calibration and mixing calculations. Accordingly, the integration and validation of SKB model output for the evolution of water chemistry during glacial cycles, and the interpretation and application to SKB's safety case, will require more detailed consideration during the main review of SR-Site. Independent geochemical modelling calculations could also support this review effort by assessing the relative importance and risk significance of mixing-related precipitation and dissolution of fracture minerals in influencing the modelled geochemical results.

SKB structured the geochemical modelling calculations in a risk-informed manner to obtain information directly relevant to the R1 safety functions in most cases, but one potential shortcoming is that the equilibration modelling did not include cation exchange processes, which may have a significant effect on the interpretation of results with respect to safety function R1(c) and the concentrations of major cations such as Ca^{2+}. SKB has acknowledged this shortcoming and has alluded to sensitivity analyses in which the impact did not appear to be significant (Salas et al., 2010, Section 9.5.3); however, more detailed complementary information to support these statements would facilitate the more detailed review of SKB's conclusions.

SKB's conceptual models for groundwater evolution describe a past and future hydrogeological setting for repeated, pervasive large-scale changes in water chemistry at the Forsmark site, including deep recharge by meteoric waters, upwelling of saline water from depth, and submergence of the site by fresh and marine surface waters. SKB also acknowledged that the modelled trend of shallow groundwater compositions in many cases diverged from observed groundwater data at these depths and stated that shallow groundwater residence times at the Forsmark site may have been too brief for equilibration to occur. Given this statement, and the overall conclusion from the geochemical modelling that the site groundwater chemistry changes pervasively over time at various depths, the discrepancy between the model predictions and the observed water compositions is potentially significant in the context of a more detailed safety review. Additional validation of the modelled results by comparison with other site data—e.g., the location, abundance, texture, and composition of Stage 4 fracture mineralization in relation to precipitation and dissolution predicted by the geochemical modelling—would support the review of the technical basis for SKB's explanations about rock–water interactions in shallow fractures and at depth. For example, a simplified set of confirmatory modelling calculations, involving mixing and equilibration with specified mineral phases, could provide an estimate of the significance of mineral precipitation in altering groundwater chemistry.

Of the six items SKB identified as R1 safety functions (SKB, 2011, Chapter 8), SKB emphasized item R1(a) (i.e., provide chemically favourable reducing conditions) as particularly important because the presence of reducing conditions in the repository contributes to the optimum performance of a number of important barriers in the safety case. SKB has described many geochemical and microbiological factors that would promote the persistence of reducing conditions over time in the repository environment. The initial review only briefly examined SKB's arguments that supported these assumptions, and this topic merits a more detailed evaluation during the main review phase based on its risk significance. In particular, it is recommended that the main review phase closely examine the assumptions associated with evolution of groundwater chemistry during glacial conditions, for which present-day examples are scarce. This includes a detailed review of the SKB modelling and the associated SKB conclusions about oxygen ingress in the rock at Forsmark during a glacial cycle (Sidborg et al., 2010).

On a related topic, the reviewers note that SKB's acquisition, screening, and use of sulphide data demonstrated a good use of site-specific data and its application to a safety function. After identifying the potential importance of sulphide in the repository environment as a contributor to container corrosion, SKB investigated, in more detail, various possible processes that could result in sulphide generation in the repository environment. SKB presented a reasoned argument to use the existing range of values from site characterization data to bound the upper limit for sulphide concentrations under future conditions. Given the risk significance associated with the uncertainty about future sulphide concentrations and the importance of the container integrity in the safety case, SKB appropriately dedicated additional effort to screening the measured sulphide concentrations in the site geochemical data to produce a high-quality data set for the safety assessment (Tullborg et al., 2010).

An initial review of SKB's data report (SKB, 2010a), geosphere process report (SKB, 2010b), and hydrogeochemical evolution report (Salas et al., 2010) identified that SKB in one way or another addressed each of the specific groundwater chemistry-related items in the R1 safety functions, typically by modelled output or by reasoned arguments based on the existing site characterization data and a discussion of expected future behaviour. However, traceability of the information and details of how the information was used in the safety assessment (e.g., as direct input to a model, or to exclude a process from detailed calculations) is not clear or concise in many examples, in part because the data were generated and reported during multiple stages of the site characterization, and in part because many of the upper-level SKB reports that are the key references supporting the SR-Site main report were written within the same narrow timeframe in 2010. The transfer of information between sources and the effect of simultaneous revisions of drafts in the SKB documents is potentially ambiguous. This raises a general question about the clarity and consistency of the integration between data, supporting models, and the safety assessment that may need additional scrutiny during a detailed review.

5. Additional comments

The initial review identified three additional topics that are of a more general nature than the topics described in the previous sections. However, additional information about each of these items would contribute to a better understanding of the information SKB has presented in SR-Site.

First, SKB acknowledged that the evolution of groundwater chemistry for glacial and permafrost conditions is uncertain in general because few present-day examples of these conditions exist, and subsurface characterizations of ice sheets and permafrost confront substantial technical challenges to avoid geochemical contamination of samples. Nevertheless, more information continues to accumulate in this topic area, and continued evaluation of the SKB conceptual model is recommended in the context of new data from current international field investigations such as the Greenland Analogue Project (Wallroth et al., 2010).

Second, SKB has identified a brackish marine groundwater component as an end-member water composition that is attributed to the submergence of the Forsmark site under the Littorina Sea during the most recent past deglaciation. The initial review was unable to identify, from the reports examined, any discussion of the origin of the Littorina Sea and how it obtained its initial high salinity. This information would be helpful in establishing why SKB has included a similar geochemical feature as part of potential future glaciation cycles and whether the proposed maximum salinity is reasonable for future conditions.

A third and final comment is the most generic. It relates to the overall hierarchy of the SKB documents that support SR-Site. According to the SKB main report (SKB, 2011, Section 2.5.12), SR-Site is structured as a main report, 16 other main references, and "about 80 additional references." SKB specified, by title and report number, the SKB reports that comprise the 16 main references (SKB, 2011, Table 2-1). These items are electronically available, along with the main report (SKB, 2011), from the SKB website,[1] where they, along with (at the time this technical note was prepared) 113 other reports, are identified on the website as "reports included in the Licence application 2011." It is not clear, either from documentation in the SKB main report, in the 16 other main references, or in the listing of reports on the SKB website, which of the 113 other reports comprise the specific "third-level" reports SKB has designated as belonging in the SR-Site hierarchy. If SKB intends for these lower-level reports to be singled out as supporting the main materials in SR-Site for review purposes, SKB needs to provide a specific listing of those documents.

6. Recommendations for main review

The initial review of groundwater chemistry has examined relevant parts of the SR-Site main report and approximately ten other supporting reports. The review concludes that SKB has implemented an appropriately risk-informed, performance-based approach to groundwater chemistry by obtaining a detailed set of site characterization data and by focusing modelling efforts on a set of geochemistry-related safety functions. The site investigations and modelling studies contributed to the completeness of the safety assessment. However, the traceability between the data-level investigations and their application to safety functions in the development of the safety case is not always clear, in part due to the large volume of information that has been accumulated over the years at the site. In particular, a more detailed evaluation of all SKB geochemical characterization information and its integration with safety function R1(a) (reducing conditions) is recommended during the main review phase as part of a risk-informed, performance-based review method.

SKB has developed a structured geochemical modelling approach to represent the geochemical evolution of groundwaters through a range of future climate states. The approach takes mixing proportions from various SKB groundwater flow models and uses these values as input data to perform mixing and equilibration calculations with the geochemical modelling code PHREEQC. The initial review finds that the general assumptions in the geochemical modelling calculations are appropriate, except that SKB has not adequated validated the assumption that omitting cation exchange processes from the model has no significant effect on the evaluation of certain safety functions. SKB's geochemical modelling method has produced useful figures that summarize the model output clearly and effectively. Nevertheless, the modelled results are closely tied to the validity and accuracy of the groundwater flow models upon which they are based. This initial review recommends a more detailed review of the input and output of the geochemical modelling files, coupled with support of the results by comparison with other site characterization data (e.g., fracture mineralization).

7. References

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APPENDIX 1

Coverage of SKB reports

Reviewed report	Reviewed sections	Comments
SKB TR–11–01: Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project	10.2.5, 10.3.7, 10.4.7, 10.4.11, 10.6.3	Also examined Sections 4.4.4, 4.8, 4.10.2, 7.5, 8.3.4, .4
SKB TR–10–48: Geosphere process report for the safety assessment SR-Site	5	Also examined Sections 1 and 6
SKB TR–10–52: Data report for the safety assessment SR-Site	6.1	Also examined Sections 2.1 and 2.3
SKB TR–08–05: Site description of Forsmark at completion of the site investigation phase: SDM-Site Forsmark	9	Also examined Sections 2.3, and 11.7
SKB TR–10–39: SR-Site – sulphide content in the groundwater at Forsmark	All	Tullborg et al. (2010)
SKB TR–10–57: SR-Site: Oxygen ingress in the rock at Forsmark during a glacial cycle	All	Sidborn et al. (2010)
SKB TR–10–58: SR-Site – hydrogeochemical evolution of the Forsmark site	All	Salas et al. (2010)
SKB TR–10–59: Aspects of geochemical evolution of the SKB near field in the frame of SR-Site	Skimmed	Sena et al. (2010)
SKB R–09–20: Groundwater flow modelling of periods with temperate climate conditions – Forsmark	3.1.4 and Appendix C	Joyce et al. (2010)
SKB R–09–21: Groundwater flow modelling of periods with periglacial and glacial climate conditions – Forsmark	1.3	Vidstrand et al. (2010)
SKB R–08–47: Bedrock hydrogeochemistry Forsmark: Site descriptive modelling: SDM-Site Forsmark	All	Laaksoharju et al. (2008)
SKB R–08–84: Explorative analysis of major components and isotopes	All	Smellie et al. (2008)
SKB R–08–86: Water-rock interaction modelling and uncertainties of mixing modelling: SDM-Site Forsmark	2.1	Gimeno et al. (2008)
SKB R–08–87: Background complementary hydrogeochemical studies	All	Kalinowski, ed. (2008)

SKB R–08–102: Fracture mineralogy of the Forsmark site: SDM-Site Forsmark	5.1.3, 6.2, 6.4, 6.5, 10	Sandström et al. (2008)
SKB R–02–49: Hydrogeochemical site descriptive model – a strategy for the model development during site investigations	Skimmed	Smellie et al. (2002)
SKB P-10-40: Forsmark site investigation – Hydrochemical monitoring of groundwaters and surface waters: Results from water sampling in the Forsmark area, January–December 2009	All	Nilsson et al. (2010)
SKB P-08-54: Forsmark site investigation – Hydrochemical monitoring of percussion- and core drilled boreholes: results from water sampling and analyses during 2007	Skimmed	Berg and Nilsson (2008)
SKB P-06-63: Forsmark site investigation – Hydrochemical characterisation in borehole KFM08A: Results from the investigated section at 683.5–690.6 (690.8) m	All	Berg et al. (2006)

APPENDIX 2

Suggested needs for complementary information from SKB

1. Provide data to confirm the characteristics of a deep saline environment at the Forsmark site, or present a discussion as to why this is not needed. Include a discussion of potential alternative conceptual models of site hydrochemistry if a deep saline end-member is not present. This information is needed because the lack of confirmation of a highly saline water at depth could alter the expected evolution of salinity near the repository horizon during glacial cycles and has implications for the initial site hydrochemical conceptual model on which the remaining geochemical modelling is based. Both these concerns relate to the geochemical safety functions that deal with total salinity and cation concentrations.
2. Provide additional information to support SKB's exclusion of cation exchange processes and silicate weathering in modelling the evolution of groundwater chemistry during future climate states. This information is needed because SKB has not provided sufficient information to support the significant discrepancies between observed concentrations of major cations and model predictions.
3. Describe whether or how SKB has addressed the potential persistence of a microbially induced "sulphide bloom" (stimulated by sulphate reduction), due to site characterization and construction activities. This information is needed because sulphide concentrations are identified as an important factor with respect to canister integrity.
4. Describe how the observed textures and abundances of late-stage (Stage 4) fracture mineralization from borehole cores at the Forsmark site correspond to the site conceptual model for paleohydrogeology, which described pervasive and repeated large-scale changes in water chemistry and mineral equilibria at various depths during the last glacial cycle and subsequent deglaciation. Because SKB has relied on the paleohydrogeology model to develop geochemical models of groundwater evolution for future climate states, this information is requested to support an evaluation of SKB's model verification.
5. Provide additional information to describe how the Littorina Sea is thought to have obtained its initial high salinity and explain why this composition is considered a bounding salinity value for future submerged conditions at the Forsmark site. This information is needed to determine whether the SKB conceptual model for groundwater evolution during glacial cycle has considered a reasonable variation of future seawater salinities in the Forsmark area.
6. Compare the SKB assumptions about groundwater chemistry beneath large ice sheets and in permafrost in the context of the accumulating data and insights that are being obtained by current field investigations such as the Greenland Analogue Project. This information is needed to supplement the SKB conceptual model for uncertain but expected conditions during glacial cycles.
7. Specify which of approximately 80 additional lower-level SKB reports directly support the hierarchy of SR-Site's main report and 16 upper-level reports. If SKB wishes to have the information in the lower-level reports considered within the hierarchy of important supporting information, SKB needs to clarify which reports are part of this group.

APPENDIX 3

Suggested review topics for SSM

1. Conduct one or more top-down reviews of the traceability of a specific set of geochemical data used in modelling that supports the safety case. The initial review has identified examples of data traceability issues that highlight the need in the main review phase for SSM to critically review and trace the accuracy of the data SKB has used to support hydrochemistry conditions important to safety.
2. Assess how SKB has addressed the cumulative uncertainties between groundwater flow models and geochemical modelling. This effort will require integration with the hydrogeological review team. SKB has addressed several of the geochemical safety functions with geochemical modelling calculations that provide detailed coverage of the Forsmark site but all of the results are derived from mixing fractions generated by the flow models. Consequently, the SSM review of the acceptability of the groundwater flow models has significant implications for the modelled evolution of groundwater chemistry.
3. Conduct a detailed review of SKB's models and reasoned arguments for the persistence of reducing conditions at the repository horizon, including the potential for deep oxygenated recharge. The safety function about reducing conditions in the repository environment has the broadest application in terms of geochemistry in SKB's safety case because reducing conditions affect canister integrity, corrosion of other metals, dissolution of spent fuel, and numerous transport parameters. The initial review highlighted the prominence of this safety function and the uncertainties associated with the potential for deep oxygenated recharge under glacial climate conditions, and recommends that additional evaluation of this issue is important for the main review phase in support of the safety evaluation.
4. Supplement the review with a simplified set of confirmatory modelling calculations (mixing and mineral equilibration) to assess the significance of mineral precipitation in altering the modelled results about the evolution of groundwater chemistry. SKB has addressed several of the geochemical safety functions with modelling calculations that define a range of concentrations of various chemical species of interest. The initial review could not find a discussion of sensitivity analyses to address uncertainties about the input or results of the modelling. A simplified set of confirmatory modelling calculations is suggested to determine whether the issue is significant enough to evaluate further during the main review phase.
5. Supplement the review with a detailed modelling analysis to assess the cumulative uncertainties between groundwater flow models for temperate periods and those for various stages of a glacial cycle. SKB has addressed several of the geochemical safety functions with modelling calculations that define a range of concentrations of various chemical species of interest. Conceptual uncertainties are greater for the glacial cycle modelling and require a closer assessment during the main review phase.
6. Each of the items listed in Appendix 2 ("Suggested needs for complementary information from SKB") pertains to a review question about SKB's site characterization data or the justification SKB has provided for verification or validation of conceptual or quantitative models. If complementary information is provided, it will need to be assessed carefully in the context of the main review. If the complementary information is not provided, the main review may need to target the topic area for a more detailed, independent assessment of the missing information.

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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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