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Swedish Radiation Safety Authority

2016:12

SSM's external experts' reviews of SKB's safety assessment SR-PSU – engineered barriers, engineering geology and chemical inventory

Initial review phase

Report number: 2016:12 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) received an application for the expansion of SKB's final repository for low and intermediate level waste at Forsmark (SFR) on the 19 December 2014. SSM is tasked with the review of the application and will issue a statement to the government who will decide on the matter. An important part of the application is SKB's assessment of the long-term safety of the repository, which is documented in the safety analysis named SR-PSU.

Present report compiles results from SSM's external experts' reviews of SR-PSU. The general objective of these reviews has been to give support to SSM's assessment of the license application. More specifically, the instructions to the external experts have been to make a broad assessment of the quality of the application within the different disciplines and to suggest needs for complementary information. The results may also be helpful in guiding SSM to detailed review issues that should be addressed in the assessment of the application.

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Project information

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Contact persons and registration numbers for the different expert review contributions are given in the report.

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Available at www.stralsakerhetsmyndigheten.se

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Bentonite in geological disposal of low and intermediate level radioactive waste

Activity number: 3030014-1004
Registration number: SSM2015-1022
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Abstract

This report has been developed as part of the initial review phase of the extension of the SFR facility. It focuses on the properties of the bentonite components of the SFR facility and their contribution to the performance and safety of the repository. The objective has been to identify the usage of bentonite in different parts of the repository, and to preliminarily comment on the scientific soundness and overall quality of SKB's reporting. Moreover the aim has been to review the evolution of geochemical and geomechanical properties of bentonite, as well as their impact on the long-term safety of the repository. Finally, potential bentonite-related issues that need to be addressed by SKB are proposed, as well as bentonite-related issues that are of importance and need to be focused on during the main review phase. Based on the reviews conducted during this initial review task, it appears that SKB has undertaken and documented a highly competent and systematic safety assessment for the SFR. SKB's documentation safety assessment is generally well structured and well written, and it seems to cover the necessary areas. The documentation also appears to be generally transparent and traceable to underlying references, although this aspect has not been tested extensively during this review task. Assessing the scientific soundness of the many and various studies that underlie the safety assessment will need to be a part of the main review. SKB's technical solutions for the disposal of the wastes are mature in the sense that SFR already exists and has been operating safely for a number of years. There is still a need though for SKB to demonstrate that the engineered barriers can be installed as designed under realistic conditions underground. SKB's assessment methodology has been developing for over a decade and has been applied in several safety assessments for different waste types (e.g. spent fuel, low and intermediate level radioactive wastes). The assessment methodology is regarded as appropriate, but SSM may wish to request further information to supplement the safety assessment.

Contents

1. Introduction

1.1. Background

On 19 December 2014, the Swedish Radiation Safety Authority (SSM) received an application from Svensk Kärnbränslehantering AB (SKB) for the expansion of its repository at Forsmark for the disposal of low- and intermediate-level radioactive waste. The repository at Forsmark is known as the SFR. SSM is tasked with reviewing the application and will issue a statement to the Swedish government who will decide on the matter. An important part of the application is SKB's assessment of the long-term safety of the repository, which is documented in the safety analysis named SR-PSU.

SSM's review of the application has been divided into an initial review phase and a main review phase.

1.1.1. The initial review phase

The initial review phase has several objectives.

- To develop a broad understanding of the application.
- To determine whether SKB's documentation is understandable and complete with regard to the information that is needed to be able to make a proper assessment of the application. SSM will ask SKB to provide complementary information on certain issues at the end of the initial review phase.
- To identify key review topics for the main review phase. These are likely to be topics that have a significant impact on the assessment of whether the application fulfils relevant requirements. Furthermore, these will be topics on which it tends to be difficult to make judgments.

General instructions for the initial review of SKB's documentation were as follows:

- Become familiar with SKB's documentation and give a brief account of the structure and most relevant parts of SKB's documentation as well as the safety relevance of the topics under review. The SR-PSU main report is important since it puts various technical areas into the context of an overarching safety analysis. If necessary, higher order references should also be consulted, keeping in mind the general objective of the initial review phase.
- Assess and briefly document the overall quality of SKB's documentation. This should, if applicable, include a brief assessment of the structure, transparency, traceability, scientific soundness, as well as maturity of SKB's technical solutions and of SKB's methodology.
- Identify any requests for complimentary information or clarifications that are deemed necessary to effectively assess the license application in depth.
- Suggest which are the most important review topics for the main review phase and describe why these are judged to be important in view of the safety assessment results. For SSM the impact of different parts of the assessment to its overall results is an important question, because this in turn is connected to regulatory compliance.

- If applicable, assess the adequacy of relevant models, data and safety functions as well as the handling of uncertainties. Merits and weaknesses of SKB's work should be identified.

1.1.2. The main review phase

The main review phase will involve detailed analysis of specific issues. The specific review tasks for the main review phase will be defined using the results from the initial review phase. The main review phase is expected to involve a structured collaboration between external reviewers and SSM staff, so that multi-disciplinary issues can be handled in a more comprehensive manner than during the initial review phase. In the main review phase, SSM will determine if SKB's application fulfils all necessary regulatory criteria.

1.2. Scope and objectives

This report has been developed as part of the initial review phase. It focuses on the properties of the bentonite components of the SFR and their contribution to the performance and safety of the repository.

The scope and objectives specified for the initial review assignment described in this report were:

- To browse through the Main Report SR-PSU (SKB 2014a, TR-14-01) to account for the structure of topics in SKB's reporting of the bentonite-related issues.
- To review the Initial State Report (SKB 2014b, TR-14-02), and relevant references therein, to identify the usage of bentonite in different parts of the repository, and to preliminarily comment on the scientific soundness and overall quality of SKB's reporting.
- To review the Engineered Barrier Process Report (SKB 2014c, TR-14-04), and relevant references therein, focusing on Chapter 7, "Silo", and Chapter 10, "Plug" for the evolution of geochemical and geomechanical properties of bentonite, as well as their impact on the long-term safety of the repository, and to make preliminary comments on the scientific soundness and overall quality of SKB's reporting.
- To make an integrated review of the above mentioned reports and other relevant SKB documents, and suggest potential bentonite-related issues that need to be addressed by SKB, as well as bentonite-related issues that are of importance and need to be focused on during the main review phase.

1.3. This report

This report is structured as follows:

- Section 2 provides an introduction to the design of the SFR and describes the uses of bentonite and bentonite-based materials and their main functions.
- Section 3 identifies and briefly describes the structure of the SKB documentation reviewed and SKB's approach to reporting on bentonite-related topics.

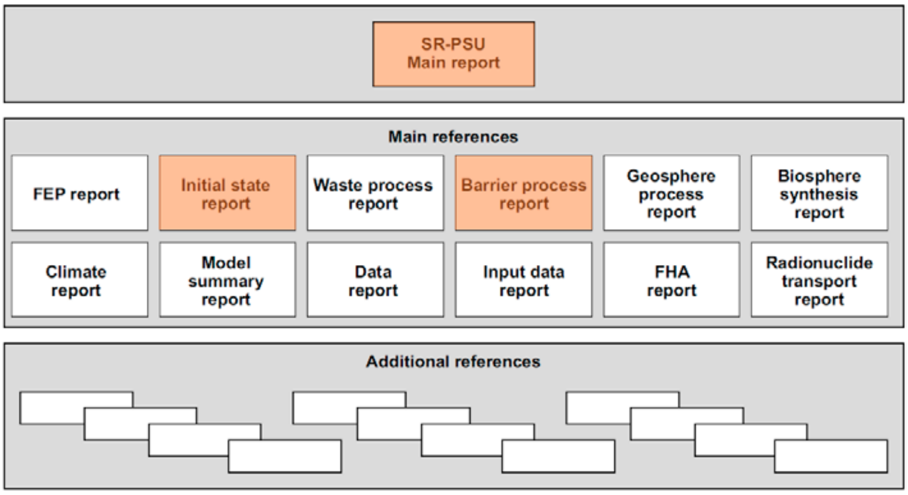
- Section 4 addresses a range of geochemical and geomechanical topics related to the bentonite-based materials used to form barriers in the repository system.
- Section 5 discusses various aspects of safety assessment focussing on the treatment of the bentonite barriers in the SR-PSU assessment.
- Section 6 summarises preliminary conclusions from this initial review task, commenting on issues such as the overall quality of SKB's documentation, the maturity of SKB's technical solutions and assessment methodology, the adequacy of SKB's assessments so far as can be ascertained at this stage, and topics that could/should sensibly be the focus of more detailed review during the main review phase.

2. SKB's documentation

2.1. Structure

The structure of SKB's documentation including the SR-PSU safety assessment is illustrated in Figure 1.1.

Figure 1.1 SKB's documentation of the safety assessment for the SFR. The main reports reviewed in this initial review task are highlighted in orange.



2.2. Content

The Main Report for the SR-PSU safety assessment (SKB 2014a, TR-14-01) is an approximately 500 page long document that addresses the following topics:

- Introductions, including a summary of SKB's system for waste disposal, background on the SFR repository, a description of the wastes to be disposed of, a summary of the applicable regulations, and an introduction to safety assessment.
- A detailed description of SKB's safety assessment methodology, introducing the safety principles and regulatory requirements, setting out SKB's ten step methodology and discussing its application over certain timescales and how uncertainties are addressed. Brief information is also given on quality assurance of the safety assessment.
- SKB's approach to the handling of FEPs (Feature, Events and Processes) and a description of how FEPs are addressed in the following areas; initial state FEPs, internal processes, external conditions.
- A description of the initial state of the repository and its surroundings, including the wastes, the repository itself, the climate, 'surface systems' (such as topography, near-surface hydrology, ecosystems, human populations and water and land uses), the bedrock, hydrogeology and groundwater chemistry.
- Safety functions.

- The ‘reference evolution’ envisaged for the repository (the climate and expected changes over the assessment period, including periods of temporate and periglacial conditions).
- SKB’s approach to the selection of scenarios for the SR-PSU safety assessment, including a ‘main scenario’, less probable scenarios, residual scenarios and scenario combinations.
- A description of the calculation cases undertaken in the SR-PSU safety assessment, including descriptions of the models and data used, and identifying the safety relevant radionuclides.
    - Within the main scenario different calculations are taken for:
        - A global warming case.
        - An early periglacial case.
        - Collective dose.
    - Calculations are undertaken for the following less probable scenarios:
        - A high inventory case.
        - A high groundwater flow case.
        - An accelerated concrete degradation case.
        - An accelerated bentonite degradation case.
        - An earthquake case.
        - A case with high concentrations of complexing agents.
        - A case with a water well downstream of the facility.
        - A human intrusion case in which a well is drilled into the facility.
    - Calculations are undertaken for the following ‘residual’ scenarios:
        - No sorption in the repository.
        - No sorption in the bedrock.
        - High water flow in the repository.
        - Alternative redox conditions in the repository.
        - Extended global warming conditions.
        - Unclosed repository.
        - Future human actions.
        - Glaciation and post-glacial conditions.
- Safety assessment results in terms of calculated results for radionuclide transport and assessed doses.
- A discussion of risk in terms of protection of human health and environmental protection.
- Conclusions, including an assessment of the need for further research and further developments in terms of waste characterisation and facility design and operation.

The Initial State Report (SKB 2014b, TR-14-02), comprises some 120 pages. It was produced as a part of the second step in SKB’s ten-step assessment methodology (i.e. ‘description of initial state’) and it details the initial state of the repository at the time of its closure. The report also describes waste acceptance criteria, the reference waste inventory, the repository reference design, and control and inspection processes that will be used to secure an appropriate initial state of SFR. Conclusions are drawn on the expected state of the repository and its environs immediately after closure for each of the eight repository vaults and for the repository plugs and closure components (see below). For example for the silo, one conclusion of the report is that ‘*the bentonite wall filling is stable and only small movements have been detected in the top filling, which indicates that the water absorption in the bentonite is insignificant*’. An appendix to the report contains detailed information on the waste packages and repository vaults.

The Engineered Barrier Process Report (SKB 2014c, TR-14-04), comprises some 340 pages. It was produced as a part of the fourth step in SKB's ten-step assessment methodology (i.e. '*description of internal processes*') and it documents available scientific knowledge on, and SKB's handling of, processes that may occur in the repository engineered barriers. The processes considered were identified by SKB as being of relevance to the long term safety of the SFR based on the findings from a previous safety assessment. The Engineered Barrier Process Report (SKB 2014c, TR-14-04) describes the repository components and their safety functions, and then uses a defined template to discuss systematically each of the thermal, hydraulic, mechanical, chemical and radionuclide transport processes that might occur in each part of the SFR. The range of processes considered is not exhaustive, but is quite broad and appears to include the most important factors that are, or could be, relevant to safety. For example, for the silo the report discusses:

- Thermal processes.
  - Heat transport.
  - Phase changes/freezing.
- Hydraulic processes.
  - Water uptake and transport during unsaturated conditions.
  - Water transport under saturated conditions.
  - Gas transport/dissolution.
  - Piping/erosion.
- Mechanical processes.
  - Swelling.
  - Stress changes, effective as well as total stress changes.
  - Deformation and settlement.
  - Failure and stability.
- Chemical processes.
  - Advection and dispersion.
  - Diffusion.
  - Sorption.
  - Alteration of impurities.
  - Colloid transport and filtering.
  - Dissolution/precipitation.
  - Concrete degradation.
  - Aqueous speciation and reactions.
  - Osmosis.
  - Montmorillonite transformation.
  - Iron–bentonite interaction.
  - Montmorillonite colloid release.
  - Microbial processes.
  - Cementation in bentonite.
  - Metal corrosion.
  - Gas formation.
- Radionuclide transport.
  - Speciation of radionuclides.
  - Transport of radionuclides in the water phase.
  - Transport of radionuclides in the gas phase.

3. Description of the SFR Disposal Facility

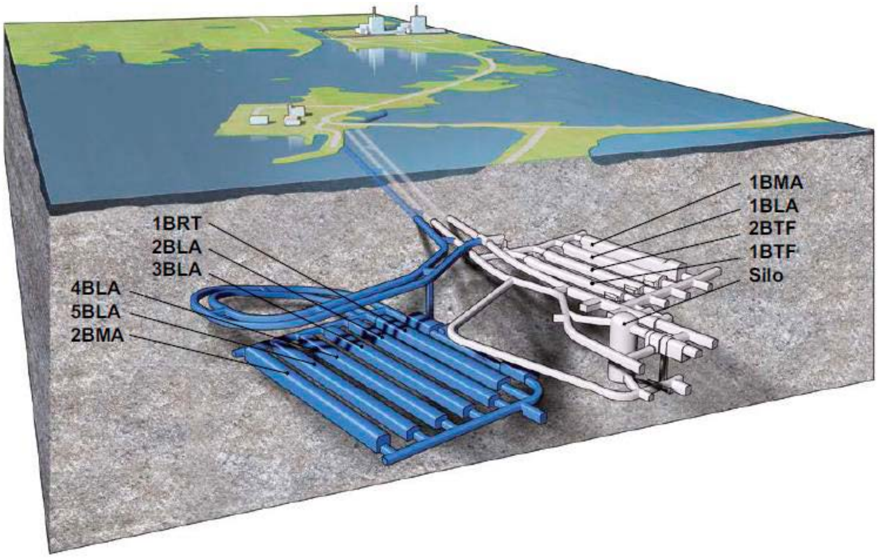
3.1. Overview of the SFR disposal facility

Sections 1.2 and 4.3 of SKB 2014a (TR-14-01) describe the SFR broadly as follows. The SFR is designed as a subsea, hard-rock facility that is accessed via tunnels from an associated surface facility.

The existing part, 'SFR 1', comprises a silo and four waste vaults for different waste categories. The waste vaults are located about 60 m beneath the surface of the sea. The bottom of the silo is located deeper, however, at ~130 m beneath the sea surface.

The extension, 'SFR 3', would comprise six waste vaults. The waste vaults in the new part of the facility would be located ~120 m beneath the sea surface, which means that they will be close to the level of the bottom of the silo, see Figure 3.1.

Figure 3.1 The existing SFR 1 (light grey) and the extension SFR 3 (blue) with access tunnels. The waste vaults in the figure are the silo for intermediate-level waste, vault 1 and vault 2BMA for intermediate-level waste, vaults 1–2BTF for concrete tanks with intermediate-level waste with low activity levels, vaults 1BLA and 2–5BLA for low-level waste and the vault 1BRT for reactor pressure vessels.



Currently, there are two access tunnels. In order that whole reactor pressure vessels can be emplaced in the repository, a third access tunnel is planned.

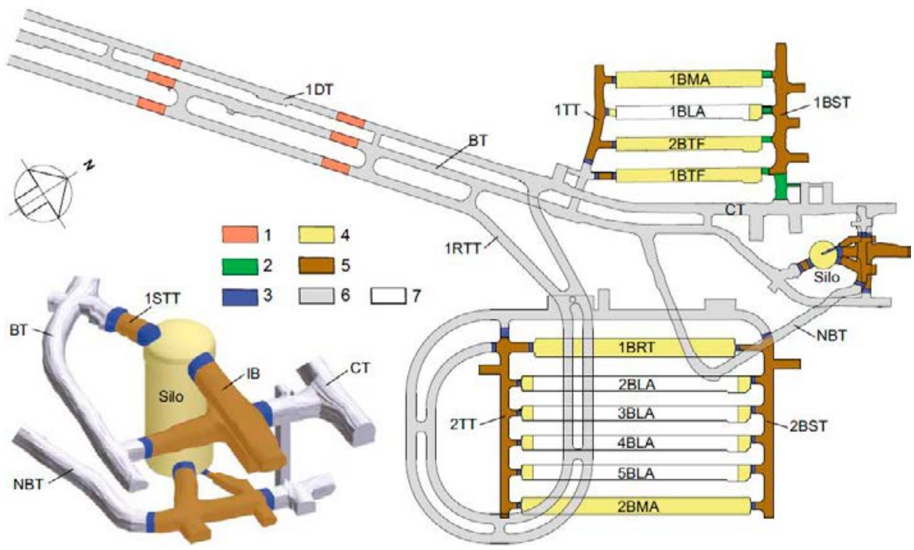
The SFR facility will be decommissioned when all waste has been disposed of. When the decision on final shutdown has been taken, decommissioning of the facility will begin and will continue until the repository has been closed and sealed. A carefully designed decommissioning plan, centred on the closure sequence, will be drawn up in good time before the closure works begin. Demolition and dismantling of existing systems will then be coordinated with the closure activities. After decommissioning and closure, the repository will be a passive system that can be left without further measures having to be taken to maintain its proper function.

Facilities above ground will be decontaminated and used for other purposes or demolished.

Closure will include installation of backfill material and plugs at selected locations in the underground facility. The primary purpose of these engineered barriers is to reduce the flow of water through the waste and impede human intrusion into the repository. Plugs are to be installed in access tunnels and connecting shafts, and all tunnels are to be backfilled with macadam. The upper part of the access tunnels is to be filled with stone blocks and sealed with concrete plugs. Finally, the ground surface will be restored so that it blends in with the surrounding landscape. In addition, all boreholes at SFR will be sealed so that the water flow in the surrounding rock is not affected by their presence.

The closed repository is illustrated in Figure 3.2. The plug sections are hydraulically tight sections with bentonite that is held in place by mechanical constraints. Wherever warranted by the geometry of the tunnels and the properties of the rock, concrete plugs are installed as mechanical constraints. Where this is not suitable, a mechanical constraint consisting of backfill and transition material is installed instead. The backfill material consists of macadam and the transition material of 30/70 bentonite/crushed rock. The role of the transition material is to hinder bentonite transport out from the hydraulically tight sections, to take up the load from bentonite swelling and transfer it to the backfill material.

Figure 3.2 Schematic plan of SFR 1 and SFR 3, with a detailed view of the silo. Key to numbering: 1) Plugs in access tunnels 2) Transition material 3) Mechanical plug of concrete 4) Backfill material of macadam 5) Hydraulically tight section of bentonite 6) Backfill material in access tunnels and the central area of the tunnel system 7) Non-backfilled openings. Note that the figure shows Layout 2.0; Layout 1.5 is used in SR-PSU modelling.



3.2. Uses and functions of bentonite barriers at SFR

Bentonite blocks, bentonite pellets and mixtures of bentonite and sand, or bentonite and crushed bedrock material are used in a number of applications for the SFR repository. The main function of the bentonite-based components is to provide a hydraulic barrier and prevent or limit water flow through the repository, which could lead to migration of radionuclides. Another important property of the bentonite-based components is the development of a swelling pressure as the material gradually becomes saturated. The swelling pressure is, in certain cases important as part of the mechanical stability of the system. The different applications of bentonite or bentonite mixtures in the SFR are briefly described in the following paragraphs.

3.2.1. The silo

The silo is built in a huge cylindrical rock cavern, which is 35 m in diameter and 70 m high, and which is located between 65 m and ~130 m below the surface. The silo itself has a diameter of 25 m and is 50 m high. Bentonite or bentonite mixed with sand or crushed rock surrounds the silo at the bottom, along the periphery and at the top. The bentonite is from Milos in Greece, but has been converted from its original Ca-form to the Na-state by soda treatment.

Bentonite at the bottom of the silo

Above the base of the rock cavern, a 1.5 m thick layer of a sand/bentonite mixture is placed. The proportions of sand to bentonite are 90/10 and it is compacted in a number of layers, resulting in a very stiff foundation. The purpose of this sand/bentonite mixture is twofold, it shall act as a hydraulic barrier and it should also constitute a firm base for the foundation of the silo and allow very little settlement. SKB's target value for the constraint modulus of the mixture was 100 to 150 MPa. Settlement during filling of the silo has been monitored (Pusch 2003) and it seems that up until 2002 (the date of the last reported observations), the target value for the constraint modulus was reached with a good margin. However, no results from measurements made after 2002 have been found during this review.

The bentonite/sand bottom bed should also have a hydraulic conductivity less than $^1/_{10}$ of the host rock, which is believed to be 10^{-8} m/s. Laboratory testing of bentonite/sand mixtures with densities similar to the bottom bed revealed values on the order of 10^{-10} m/s, which are well below the required values.
The swelling pressure of the bottom bed has been estimated through laboratory tests and found to be on the order of 50 to 100 kPa, which means that it will have very little impact on the movement of the silo.

Bentonite around the periphery of the silo

The bedrock walls are covered with shotcrete, which also contains a system of drains. The space between the shotcrete and the silo is filled with bentonite pellets, which are not compacted. The purpose of the bentonite pellets is to act as a hydraulic barrier and, in the longer term, to support the silo and the surrounding rock mass with a swelling pressure. The recommended minimum value of the hydraulic conductivity here is also $^{1}/_{10}$ of that of the surrounding rock mass and, thus, it should be less than 10^{-9} m/s. Testing of the bentonite at the densities expected has shown that the hydraulic conductivity in all parts of the bentonite is expected to be equal to, or less than, 10^{-10} m/s.

Bentonite swelling pressures and densities have been measured a number of times since emplacement and are reported in Pusch (2003). The bentonite pellets are far from saturated, and so far the swelling pressures have been well below the maximum values of 500 kPa. The swelling pressures also appear to be far more uniform than assumed in the design. However, no results from measurements after 2002 have been found, either for the degree of saturation, or for swelling pressure.

Bentonite at the top of the silo

The silo is closed with a number of concrete lids on top of which 1.5 m of a sand/bentonite mixture will eventually be compacted. The purpose of this bentonite/sand mixture is mainly to act as a hydraulic barrier, but it is also intended to support the frictional material filling the void above the silo. No information on the criteria for this sand/bentonite mixture material has been found.

3.2.2. The plugs and transition zones

With the exception of the silo, each of the different parts of the SFR, that is all the BLAs, both BMAs, both the BTFs and the BRT, are to be closed off by a concrete plug at one end and transition material, consisting of a 30/70 mixture of bentonite/crushed rock, at the other end. The silo is closed off by a number of plugs incorporating a bentonite section between two concrete plugs.

The concrete plugs constitute a mechanical boundary for the vault, and the bentonite/crushed rock constitutes a first hydraulic barrier and also, in some cases, a transition to the bentonite in the tunnels.

The transition zones are supposed to have a hydraulic conductivity of 10^{-9} m/s to 10^{-11} m/s, depending of the density of the mixture. These hydraulic conductivities are based on laboratory test results, but the possibility of achieving these values in full scale testing is yet to be demonstrated.

The tight sections, which are constituted from bentonite blocks, have a target hydraulic conductivity value of 10^{-12} m/s to 10^{-13} m/s for an average emplaced dry density of 1,400 kg/m^3. It should be possible to achieve these hydraulic conductivity values, but it needs to be demonstrated that the densities can be achieved not only in a dry tunnel, but also if some water leaks in to the tunnel during operations. Another important question is how the Excavation Disturbed or Damaged Zone (EDZ) is to be dealt with during plug design and construction, both conceptually and in practice.

3.2.3. The access tunnels

The access tunnels immediately outside the different repository tunnels are to be filled with bentonite. The bentonite will be emplaced in the form of compressed blocks, and the space between the blocks and the bedrock wall will be filled with bentonite pellets. These parts of the tunnels shall function as hydraulically tight sections. In the access tunnels, between each part of the repository there will be one area where according to SKB the EDZ will '*be removed'* in order to stop parallel flow of water in the EDZ. Again, more detail is needed on how this will be done in practice.

3.2.4. Sealing of boreholes

A number of boreholes intersect the repository area and these need to be sealed and closed off. SKB has suggested two different methods and both are supposed to function even for rather deep boreholes. Highly compacted bentonite is used where tight seals are needed and cement-stabilized plugs are cast where the boreholes pass through fracture zones. In our view there should not be any real difficulty in sealing intact boreholes, but there could be more problems for anomalous or 'failed' boreholes, and alternative methods might be needed.

4. Bentonite processes and interactions

This section discusses various processes that have been identified by the reviewers as being likely to be of the greatest relevance to the performance of the bentonite-based barriers in the SFR design and to the overall safety of the disposal facility. The processes discussed below include both physical/geomechanical processes and chemical/geochemical processes as these areas were defined as the main focuses of this initial review assignment. In detail, however, there are often couplings between different processes (e.g. between chemical and mechanical processes). The selection of the processes discussed below has been made on the basis of the experience and expert judgement of the reviewers regarding which processes may be the most significant.

4.1. Bentonite processes

4.1.1. Hydraulic saturation

The time required to achieve full saturation of the different bentonite applications discussed in Section 3 will vary considerably, depending in particular on the percentage of bentonite in the material and on the hydraulic conductivity of the materials and the surrounding rocks. The saturation and evolution of several of these applications of bentonite-based materials in the SFR has not yet been modelled. SSM should consider requesting SKB to provide a more complete set of modelling analyses that examines the properties, behaviour and evolution of each of the bentonite-based barriers in the SFR in order to allow more meaningful reviews to be undertaken.

4.1.2. Swelling

The achievement of suitable bentonite swelling pressures is crucial, particularly for the proper functioning of the bentonite pellets surrounding the silo. The swelling pressure needs to be larger than 100 kPa, but not larger than 500 kPa. So far, as reported by Pusch (2003), no pressures outside the admissible pressure range have developed. Once the volume of bentonite pellets has been saturated, the swelling pressures should be rather uniform, as long as only limited piping and erosion have taken place. Full saturation should occur long before the concrete silo deteriorates and, thus, the structure of the whole design should remain intact. However, some 13 years have elapsed since the last swelling pressure measurements were reported and it is extremely important to ensure that the swelling pressures have not changed radically during this period. Thus, more recent monitoring data ought to be reviewed.

4.1.3. Hydraulic conductivity

As part of the repository design process, target values are given for the hydraulic conductivities of each of the different applications of bentonite-based materials in the SFR (e.g. the tight sections, the transition material, the filling around the silo, the beds below and above the silo, the access tunnels and the borehole seals). The material densities specified do correspond to, and should provide, the desired hydraulic conductivities, but it remains to be shown that these densities can be obtained under practical working conditions.

4.1.4. Piping and erosion

During repository operations, including during waste emplacement, very little bentonite is in place (currently only the sand/bentonite mixture below the silo and the bentonite pellets surrounding the silo walls). The drains along the bedrock walls of the silo minimize the hydraulic gradients and should, therefore, limit the likelihood of piping or erosion. For tunnels filled with bentonite blocks a substantial flow of water from the bedrock could be problematic. First, it might jeopardize the efficient placement of the bentonite blocks if they start to swell too early in the process. It might also cause unwanted flow of water eroding small particles of bentonite.

Many years after the repository is closed when all of the bentonite-based materials have become fully saturated, hydraulic gradients in and around the SFR will be very small. In this fully-saturated condition and with low hydraulic gradients there should not be any piping or physical erosion of bentonite.

Therefore, the critical phase during which piping and erosion of bentonite around the silo might occur is the transient period after the silo has been filled and closed off and the pumping has just been stopped. If the water flow from the bedrock is substantial, the drains will fill up rather quickly, and a large hydraulic gradient might develop across the compacted sand/bentonite foundation bed. As the bentonite content in the foundation bed is only 10%, it is prone to internal erosion and piping. The bentonite pellets could also be harmed by piping and erosion, and here also large hydraulic gradients might develop in the early phase after pumping is stopped. It will be important, therefore, to carefully manage the process of stopping the pumping and, thereby, control the gradual filling of the drainage system around the silo in order not to allow too large hydraulic gradients.

SSM should, therefore, consider making a more detailed review of the likely water inflows to the repository, and should also consider requesting further information from SKB on its plans for the cessation of pumping and managing the transition from operating conditions to long-term post-closure conditions.

4.1.5. Freezing

The consequences and potential problems related to freezing of bentonite at the SFR are addressed, for example in Emborg et al. (2007), SKB 2014c (2014-14-04) and SKB 2014f (R-14-29), and various scenarios are described in SKB 2014a (TR-14-01, Section 5).

SKB (2014f, R-14-29) notes that:

- The influence and extent of possible frost-heave in the silo has been quantified under the assumption that the material is frost susceptible and that no density redistribution occur as a consequence of freezing. The results suggest that no damaging pressures will develop in the silo due to ice-lens build up, but that the extent to which the silo bentonite will selfheal after ice lenses thaw remains an open question. Page 380 of SKB 2014a (TR-14-01) indicates that, '*A finite element calculation of the self-healing (after an ice-lens formation) of a spherical void with the radius 0.5 m, which would represent severe damage to the bentonite caused by piping and erosion, has been done (Cronstrand 2014). Although the results cannot be used without reservations, they indicate that the bentonite would be fairly unaffected close to the concrete silo, which means that the sealing function would remain effective. This process should however be given further attention, since the self-sealing ability is crucial and both model capabilities and material data relevant to the silo bentonite are somewhat lacking.*' It has not been possible to review and evaluate the cited reference (Cronstrand 2014) in any detail during this initial review task.

- The redistribution of silo bentonite density as a consequence of freezing has been quantified based on the expected osmotic response and the assumption of having a frictionless system. This analysis shows that, instead of forming ice in the bentonite, it may be possible for substantial density redistribution to occur.
- The effect of frost weathering (i.e. the effect of "trapping" unfrozen bentonite water within frozen surroundings, which then transforms into ice as temperature is lowered further) may give rise to possible pressure peaks. An estimation of maximum pressure has been made based on considering mechanical and chemical equilibrium between bentonite and ice, and assuming a simple elastic mechanical response. The results suggest that pressure peaks on the order of several tens of MPa cannot be ruled out.

It is concluded that freezing of bentonite at SFR may result in several complex effects, including transient pressure increases, in redistribution of bentonite mass and, in the longer term, in increased hydraulic conductivities. This initial review has not been able to trace all of the detailed quantifications and arguments around these processes and it is suggested that bentonite freezing and its effects could form the subject of a more detailed review.

4.2. Bentonite interactions

4.2.1. Interactions with swelling wastes

The wastes to be disposed of at the SFR include various organic materials. Of these, bitumenized ion exchange resins, in particular, may undergo swelling. Bitumenized wastes are allocated to the silo and to the BMA and BLA vaults.

The Waste Process Report (SKB 2014e, TR-14-03) discusses various processes related to bitumenized wastes. Bitumen is a complex mixture of high molecular, polycyclic, aromatic hydrocarbons and can be produced in a range of qualities with different mechanical properties, ranging from low-viscosity, soft bitumens to hard plastic-elastic bitumens. Only soft bitumens are used for wastes emplaced in the SFR.

Bitumen is used to solidify ion-exchange resin wastes. These wastes contain variable amounts of evaporator salts. In the bitumenization process, waste is mixed into hot bitumen resulting in a bitumen matrix containing a dispersion of embedded waste particles. Although pure bitumen is hydrophobic, water can still be transported into a bitumen matrix due to the presence of electrolytes. In pure bitumen the rate of water uptake is very low, since the driving forces are very small.

However, the bitumenized ion exchange resins and evaporator salts are hygroscopic, and the driving force for the diffusion of water into the bitumen matrix is much stronger.

In addition to chemical composition, the mechanical properties of bitumen are also affected by radiation, the production of gas within the waste matrix, and temperature. Thus, the swelling behaviour can differ markedly between different types of bitumenized waste.

SKB 2014e (TR-14-03) notes that investigations of radioactive bitumen stored for 25 years under atmospheric, oxidising conditions showed significant aging to a depth of about 5 cm from the surface. The aged material was hard, very brittle and full of small fissures. The changes in the bitumen matrix had an indirect effect on the uptake of water and subsequent swelling. Experiments with bitumenized ion-exchange resins showed that irradiated resins had an order of magnitude faster water uptake than un-irradiated resins. However, because of the conditions under which these investigations were made, these findings are probably more relevant to the operational phase.

During the post-closure phase, when there is expected to be an absence of oxygen, the primary product of radiolytic decomposition will be hydrogen gas (i.e. hydrogen may make up ~95% of the gases produced) formed by cleavage of carbon-hydrogen bonds. SKB (2014e, TR-14-03) notes that CEA (2009) estimated a hydrogen yield of 1×10^{-3} to 1×10^{-2} m^3/drum/year. It can, however, be difficult to extrapolate with confidence, between different types of bitumenized wastes, and the actual proportions and amounts of gases that could form in the SFR will be dependent on the particular wastes emplaced and the prevailing conditions.

The production of hydrogen gas within the waste may cause swelling of the bitumen matrix. The degree of swelling will depend on several factors including, the properties of the bitumen, temperature, the waste loading, the homogeneity of the waste product, and the degree of containment and confinement provided by, and voidage present in, the surrounding materials and structures (e.g. the waste package).

In the bitumenization process, a void space is left in the waste package to make room for the additional volume. Nonetheless, SKB (2014e, TR-14-03) notes that swelling due to water uptake by bitumenized waste gives rise to mechanical stresses in the waste form and that excessive swelling may lead to mechanical stresses on the surrounding packaging and engineered barriers. For an analysis of such impacts the reader of the Waste Process Report is referred to Section 4.3.1 of that report, but, unfortunately no further information on the consequences of the swelling of bitumenized wastes are provided. The final section of SKB 2014e (TR-14-03) indicates that '*knowledge of swelling pressure as a function of expansion volume is used to evaluate how much pressure structures and barriers surrounding bituminised waste will experience*', but how this is done is not apparent. There may, thus, be a need to obtain more information and review in more detail the potential impact of swelling of the waste particularly on the ability of the bentonite pellets surrounding the silo to provide the appropriate swelling pressures and fulfil their hydromechanical functions.

4.2.2. Interactions with cementitious materials

The design of the SFR includes many interfaces between cementitious materials and bentonite-based materials (e.g. Figure 3.2). Various studies have highlighted interactions that can occur at such interfaces and some have expressed concern that the mineralogical composition of the bentonite will not be stable under the hyper-alkaline pore fluid conditions (pH > 12) typical of cement and that the properties of the bentonite will degrade over long time periods (e.g. Savage et al. 2002; Gaucher and Blanc 2006).

Section 7.4.10 of the Engineered Barrier Process Report (SKB 2014c, TR-14-04) addresses the transformation of montmorillonite in the bentonite-based components as follows, '*Under typical groundwater conditions, there are a range of possible montmorillonite transformations that could lead to* [the formation of] *minerals with the same basic atomic structure as montmorillonite but decreased ability to swell. In the Silo of SFR, the bentonite is placed between concrete components, and relevant transformations of montmorillonite (and any accessory silicate minerals present) will be driven by contact with highly alkaline solutions. While it is clear that montmorillonite transformation is relevant in the presence of highly alkaline solutions, there is great uncertainty regarding reaction pathways and products as well as regarding extent or kinetics of the transformation reaction. To a significant part, this uncertainty results from the kinetic control of the process.*'

SKB (2014a, TR-14-01) notes that '*modelling performed by Cronstrand (2014) indicates that as long as the concrete wall is fairly intact, the degradation proceeds slowly. Fractured concrete on the other hand, resulting in extensive exposure to fresh cement pore water, can have a significant corrosive effect on the montmorillonite. The major uncertainties can be traced to the selected thermodynamic database, the growth kinetics of newly formed phases and unknown factors that may reduce the swelling pressure and thereby allow local flow through the bentonite barrier. These areas will be studied further to add confidence to the assessment*.'

SKB, thus, clearly recognises that various interactions and mineral transformations may occur at cement-bentonite interfaces, but also very much highlights the associated uncertainties. Although a scenario and set of calculation cases has been defined for 'accelerated bentonite degradation', it is not clear from the description of this scenario given in Section 7.6.4 of SKB 2014a (TR-14-01) that the scenario can be used to represent the effects of degradation at *interfaces* between the cementitious and bentonite-based components within the repository system. It is not clear at this stage, therefore, that the uncertainties associated with cement-bentonite interactions have been properly taken into account in the SR-PSU safety assessment. This is, therefore, a topic to which SSM may wish to return during the main review phase.

5. Safety assessment

This section discusses various aspects of the safety assessment relating to the objectives of this initial review task and the bentonite-based barriers at SFR. The discussion broadly follows the steps in SKB's assessment methodology.

5.1. Assessment methodology

SKB has followed essentially the same assessment methodology for the SR-PSU assessment as it did for the assessment of spent fuel disposal in the SR-Site assessment (SKB 2010). The methodology involves ten steps (see Figure 2-4 of SKB 2014a, TR-14-01) including, (i) the handling of FEPs, (ii) description of the wastes, disposal facilities (existing and planned) and the site, (iii and iv) consideration of internal and external processes, (v) the definition of safety functions, (vi) the compilation of data, (vii) analysis of the reference evolution for the site, (viii and xix) the selection and analysis of scenarios, and finally, (x) conclusions regarding safety, the need for R&D and the identification of requirements on facility design and operation.

The methodology is appropriate, but in our view provides relatively little information on the justification of the design of the facility or its optimisation. For example, during this initial review we have not found much information that explains the reasons for the proposed designs of the bentonite-based barriers to be constructed for SFR 3 or that demonstrates that they will be mechanically stable. Similarly, few details are given on why particular engineered barrier materials (e.g. sand-bentonite mixes) have been chosen. It seems entirely reasonable to ask not only would the proposed design be safe (which is certainly addressed in the safety assessment), but also is the proposed design optimal in some sense (the 'best' that can be achieved without incurring unreasonable costs etc.)? Section 4 of SSMFS 2008:37 states that, '*Optimisation must be performed and the best available technique shall be taken into consideration in the disposal of spent nuclear fuel and nuclear waste*.' It may well be that SKB has further documentation that would help to address such questions relating to design choices and optimisation, but we have not been able to find details on this topic during this initial review task.

5.2. Assessment endpoints

SKB's safety assessment principally addresses and quantifies radiological doses and risks to humans. Exposures of non-human biota to radiation have also been estimated (SKB 2014a, TR-14-01, page 367), but for an assessment of the risks from non-radiological toxic substances in the wastes (heavy metals such as cadmium, chromium, lead, or organics such as phenols, tributyl phosphate etc), the reader is referred to the Environmental Impact Assessment (EIA) (SKB 2014d), which is reported in Swedish. As the nature of an EIA is often somewhat different to that of a post-closure safety assessment, SSM may wish to review the consistency of the approaches taken for the assessments of the impacts of radionuclides and of non-radiological species.

5.3. Functions, initial state & evolution of bentonite-based barriers

5.3.1. Functions

Aspects of the bentonite-based barriers considered in the safety assessment include the provision of mechanical stability, limiting advective transport, and promoting sorption (SKB 2014a, TR-14-01, Table 5-2). The safety function indicator attributed to the bentonite-based materials of the silo and plugs is, however, defined in terms of providing low hydraulic conductivity, which contributes to the safety function 'low flow in the waste vaults' and the safety principle 'retention of radionuclides' (SKB 2014a, TR-14-01, Table 5-3).

In terms of the assumed/assessed importance to safety of the engineered barriers, it is notable that according to SKB, the bentonite components are only really considered important for the silo (SKB 2014a, TR-14-01, Table 11-1).

5.3.2. Initial state

As described above, the silo is made of *in-situ* cast concrete and is founded on a bed of sand and bentonite. The concrete silo is also surrounded by bentonite, which limits the flow of water through the wastes within it. The function of the flow barrier has been studied by Abarca et al. (2013). In the silo, the radioactive waste is deposited in a cylindrical concrete structure. Concrete walls divide the interior of the silo into disposal shafts. The waste in the silo is conditioned in cement, bitumen or concrete. The waste packages in the silo are continuously grouted during the operational phase. The entire concrete silo and its interior – including grout, concrete packaging and conditioned waste – serve as mechanical elements that resist the swelling pressure from water-saturated bentonite, the pressure from gas formation and the load from self-weight. The silo top seal is designed to release gas in order to avoid gas driven advection. In conjunction with closure, the top part of the silo cupola will be backfilled with macadam to protect against rock fallout. The bottom bed of sand and bentonite has primarily a mechanical function. The pH-buffering function of the concrete and the grout keeps gas production due to microbial activity and iron corrosion low. The choice of concrete as an engineering material also ensures good sorption properties.

In order to restrict water flow through the waste vaults, the tunnel sections closest to the vaults will be sealed with sections of bentonite. These sections are supported by mechanical plugs.

5.3.3. Evolution

After closure, the engineered structures, including the barriers composed of bentonite-based materials are assumed to slowly become hydraulically saturated. In the safety assessment, the saturation process is assumed to be instantaneous following closure (SKB 2014a, TR-14-01, page 144). As noted above (Section 4.1.1) this is not a fully realistic assumption and the implications of slow re-saturation should perhaps be considered by more detailed modelling studies.

Page 151 of SKB 2014a (TR-14-01) indicates that during the first thousand years after closure water flows through the repository vaults increase by approximately two orders of magnitude on going from submerged conditions to on-shore conditions. According to SKB, this is the most important process affecting the flow through the repository during this period. During the first thousand years after closure, degradation processes start to influence the hydraulic properties of concrete structures and materials in the repository (SKB 2014a, TR-14-01, section 6.3.8). SKB's analyses suggest that the resulting effect on groundwater flow through the repository is small, however, compared with the increase in flow due to the retreating shoreline. The hydraulic properties of the bentonite barriers in the repository are assumed not to change during the first thousand years after closure (SKB 2014a, TR-14-01, page 151).

In the longer-term (i.e. more than 1,000 years after closure) SKB's assessment assumes that the hydraulic conductivity of cementitious repository components increases until a 'completely degraded' state is reached when the concrete no longer provides a barrier to water flow. A similar approach has been taken for representing the effects of degradation of bentonite seals in tunnels at the ends of the vaults, and 'complete' degradation is estimated to lead to an order of magnitude increase in flow in the 1BMA and BTF vaults. In contrast, water flows through the silo are assumed to remain more or less constant because the silo is assumed to remain protected by its surrounding bentonite barrier (SKB 2014a, TR-14-01, section 6.4.5), which emphasises the importance attached to the bentonite barrier around the silo. This discussion suggests that SSM should consider a more thorough review of the modelling of flow through the engineered barriers as they progressively degrade, including a more detailed examination of the assumptions data and models (e.g. in Abarca et al. 2013) than has been possible in this initial review task.

SKB (2014a, TR-14-01, section 6.5.2) notes that during periods of periglacial conditions, it is possible for temperatures to be low enough for the entire repository to freeze. A ground temperature below 0°C at repository depth cannot be ruled out during the first possible occurrence of permafrost between 17,500 AD and 20,500 AD in the early periglacial climate case ground temperature of –3°C or less at repository depth cannot be ruled out during the occurrence of permafrost around 52,000 AD both in the early periglacial climate case and the global warming climate case. Under periglacial climate conditions, the most relevant scenarios for the SFR area predict significantly lower total flow through the waste vaults, longer path lengths and travel times, and higher flow-related transport resistance values compared with the values under temperate conditions. However, the results are dependent on the extent and number of taliks in the flow domain, and some of the waste vaults may experience small increases in total flows under periglacial relative to temperate conditions. The possible consequences of bentonite freezing have been briefly mentioned above in Section 4.1.5.

5.4. Bentonite degradation scenario

Section 7.6.4 of SKB 2014a (TR-14-01) describes a bentonite degradation scenario. The bentonite degradation scenario is based on an assumption that the safety function '*low flow in waste vaults'* deviates from the main scenario due to uncertainties in the consequences of extensive periglacial conditions in combination with uncertainties in the sealing properties of the bentonite. SKB assesses the probability of this scenario to be low, considerably less than 10%.

In the bentonite degradation scenario, the effects of the ice-lens formation are assumed to be so large that the bentonite surrounding the silo will have a permanently increased hydraulic conductivity, which results in an increase in water flow. It is further assumed that ice-lens formation occurs during the first permafrost period in the early periglacial climate case (i.e. in the period from 17,500 to 20,500 AD).

SKB argues that the concrete will not freeze as the temperature needed for concrete to freeze is lower than the temperature needed for bentonite to freeze. SKB also argues that the size of the plugs implies that harmful ice-lens formation could not occur and hence treats the plugs in the same way as in the main scenario. No more detailed justifications for these assumptions have been seen however.

A calculation case was set up to evaluate the influence of an ice-lens on the flow in the silo (Abarca et al. 2013). In the model, the affected bentonite barrier was simulated by defining a ring of high permeability material, surrounding the silo concrete structure at mid-height. The results suggested an order of magnitude increase in flow in the degraded volume, whereas the flow increase in the rest of the silo was moderate. The silo concrete structure limited the amount of water that could penetrate the waste.

SKB argues that this scenario can also be seen as representative for other bentonite degradation processes, for example montmorillonite alteration due to interactions with cementitious materials. As noted above in Section 4.1.5, however, this latter argument in particular does not at first sight seem particularly sound and further review may be needed.

5.5. Assessment results

Section 9 of SKB 2014a (TR-14-01) summarises the many results from the safety assessment calculations. The results are presented in terms of assessed potential annual dose and the contributions of different radionuclides to peak dose are tabulated.

Results for the bentonite degradation scenario (peak potential annual dose of 5.9 μSv at 6,250 AD, dominated by releases from the silo and by Mo-93 and C-14) (SKB 2014a, TR-14-01, Table 9-6) are broadly similar to those for the global warming variant – having a slightly earlier and higher peak and a very slightly lower tail in the long-term.

Results for the residual high flow in the repository scenario, in which both the concrete and bentonite barriers of the repository were assumed to have degraded properties from the start of the assessment, are almost one order of magnitude higher than those for the global warming variant (peak potential annual dose of 46.9 μSv at 5,000 AD, dominated by releases from the silo and by Mo-93, C-14 and Ni-59) (SKB 2014a, TR-14-01, Table 9-13).

Tables 9-20 and 9-21 of SKB 2014a (TR-14-01) together provide a useful summary of the assessment results for all of the scenarios considered. These tables help to put the results for the bentonite degradation and engineered barrier related scenarios into a wider context. For example, they show that higher peak potential annual doses are calculated for several of the intrusion wells scenarios, although these scenarios are attributed very low probabilities and, hence, lower risks (SKB 2014a, TR-14-01, Tables 10-1 and 10-2).

It is important to remember that although using safety assessment calculations to identify which radionuclides are key to dose and risk is a sensible practice, it can also be misleading if the many assumptions upon which that calculations are made are not taken properly into account. For example, SKB 2014a (TR-14-01, page 367) states, '*The relative contributions of individual radionuclides to the total risk from the repository depend on a number of factors, including the initial inventory of the radionuclides in the wastes, the capacity of the different waste vaults for retention and retardation of the different radionuclides, the behaviour of released radionuclides in the geosphere and biosphere, and the radiotoxicity of the radionuclides. In addition, the estimates of relative risk for individual radionuclides is influenced by the degree of pessimism inherent in the assumptions made in the assessment; i.e. assumptions used to model processes and values assigned to model parameters. Hence, a ranking of the radionuclides in terms of their contribution to the total risk will be conditioned by all above-mentioned factors, and should be seen as valid only for this specific assessment including its pessimisms, i.e. the results do not necessarily represent the ranking of the "actual" risks'*. Therefore, drawing conclusions as to which are the most important factors in a safety assessment is a complex task that cannot necessarily be made from safety assessment results alone and often requires expert judgement.

These caveats notwithstanding, SKB (2014a, TR-14-01, page 368) notes that different radionuclides contribute to the total risk at different times:

- Based on activity and radiotoxicity, Ni-63 is one of the most important radionuclides. However, because of its short half-life, Ni-63 will decay to insignificant levels during the time when the repository is covered by the sea. The low hydraulic gradient under the sea, resulting in low groundwater flow, means that significant amounts of Ni-63 cannot be transported to the biosphere.
- Based on radiotoxicity, Am-241 is the most important radionuclide. However, Am-241 is highly immobile under undisturbed repository conditions, i.e. high pH and reducing conditions, which means that its contribution to the radiological risk is small. Since the half-life of Am-241 is relatively short, most of the inventory of Am-241 is expected to decay during the first 1,000 year period, the time at which it is assumed by SKB that the repository might first be disturbed by a drilling intrusion. On this basis SKB argues that the potential impact of Am-241 released from the repository via an intrusion well is limited.
- During the first 20,000 years, the inventory of Mo-93 and C-14 decreases significantly due to decay. The flow-limiting function of the concrete material in BMA will be maintained for at least this period, and longer for the silo. Thereafter, the possible contribution to radiological risk from these radionuclides is insignificant due to their radioactive decay.
- After 50,000 years, freezing of the concrete barriers in the repository may occur. Further, ice-sheet development cannot be excluded. At that time, the activity of radionuclides in the repository is completely dominated by the limited amount of long-lived radionuclides with a half-life so long that they will not decay substantially during the assessment period.
- At the end of the assessment period (i.e. 100,000 years), the levels of all of the disposed radionuclides are close to, if not below, clearance levels.

Given this discussion, it would appear that important assumptions include:

- The period for which the repository is assumed to remain undisturbed (i.e. the 1,000 or 3,000 year period depending on the scenario in which there is assumed to be no human intrusion), and
- The time after which the repository might suffer damage due to ice sheet development.
- The probabilities assigned to the scenarios.

Even so, an important point to note is that according to SKB 2014a (TR-14-01, page 369), '*The contribution from uranium progeny to the total risk is not projected to increase significantly beyond 100,000 years*'. Thus, although SKB cannot exclude the possibility that permafrost may reach repository depth, or that future ice-sheet development may have a severe impact on the protective capability of the repository, limitation of the amount of long-lived radionuclides that are disposed of (i.e. Waste Acceptance Criteria) ensures that regulatory requirements for the protection of human health and environment are met even after such events. This limitation of the inventory of long-lived radionuclides is also used by SKB to justify the depth of the proposed repository extension (SKB 2014a, TR-14-01, page 369).

5.6. Conclusions (safety, R&D & operational controls)

The central conclusion of the SR-PSU safety assessment is that the extended SFR repository (SFR 1 and SFR 3) meets the regulatory criteria on long-term safety (SKB 2014a, TR-14-01, page 365). It has not been the purpose of this initial review to take a definitive view on this conclusion; that will be SSM's task at a later stage of the review.

SKB is proposing to undertake various further R&D studies (SKB 2014a, TR-14-01, Section 9) and to define and implement operational controls, including Waste Acceptance Criteria (WAC). For example, SKB notes on page 380 of SKB 2014a (TR-14-01) that the assessment of swelling of waste in the silo is handled by "*ensuring expansion volume when grouting the waste and by the method for closing the repository*". Exactly how this is and will be done is unclear. SKB also proposes to define WAC in order to control the potential effects of waste swelling in 1-2 BMA. It is suggested that SSM considers a more detailed review of the WAC and of the swelling of wastes, and the complex relationships between waste swelling, the assessed performance and safety of the disposal facility, and the possible need (or otherwise) for WAC in terms of operational procedures for waste conditioning and for closing of the silo. It is notable that, at the same time as proposing to manage the issue through the use of WAC, SKB is also planning to conduct further research studies to investigate the properties of waste forms containing ion-exchange resins and / or evaporator concentrates. It is suggested that SSM ought to keep abreast of such research.

6. Conclusions

6.1. Preliminary assessment of SKB's documentation

Based on the reviews conducted during this initial review task, it appears that SKB has undertaken and documented a highly competent and systematic safety assessment for the SFR. SKB's documentation safety assessment is generally well structured and well written, and it seems to cover the necessary areas.

The documentation also appears to be generally transparent and traceable to underlying references, although this aspect has not been tested extensively during this review task. Assessing the scientific soundness of the many and various studies that underlie the safety assessment will need to be a part of the main review.

SKB's technical solutions for the disposal of the wastes are mature in the sense that SFR already exists and has been operating safely for a number of years. There is still a need though for SKB to demonstrate that the engineered barriers can be installed as designed under realistic conditions underground.

SKB's assessment methodology has been developing for over a decade and has been applied in several safety assessments for different waste types (e.g. spent fuel, low and intermediate level radioactive wastes). The assessment methodology is regarded as appropriate, but SSM may wish to request further information to supplement the safety assessment (e.g. related to optimisation).

6.2. Possible focus of reviews in the main phase

Based on the reviews conducted during this initial review task, the following table summarises the suggestions that have been made regarding potential areas for more detailed review during the main review phase.

Potential review topic	Significance
Detailed review of water flow through the repository, including: • Review of the assumptions, data and models used to simulate degradation of bentonite and cementitious engineered barriers and the effects of barrier degradation on flow. • Review of the representation in the safety assessment of localised effects on water flow of bentonite-cement interactions. • Review of how the plugs that are intended to seal the EDZ will function hydraulically when the bentonite deteriorates.	Calculated potential doses due to radionuclide transport via the groundwater pathway are, in general, directly related to the amounts of water flow.

Potential review topic	Significance
The properties and behaviour (e.g. swelling) of bitumenized wastes in the silo and the potential hydromechanical effects of such swelling on the bentonite around the silo.	SKB's assessment assumes that water flows through the silo remain more or less constant in the long term (after 1,000 years) because of the surrounding bentonite barrier. This is a key assumption on which the safety assessment depends.
The effects of bentonite freezing, including transient pressure increases, redistribution of bentonite mass and increased hydraulic conductivities and water flows.	SKB's assessment assumes that water flows through the silo remain more or less constant in the long term (after 1,000 years) because of the surrounding bentonite barrier. This is a key assumption on which the safety assessment depends.
Detailed review of the potential for piping and erosion of bentonite-based barrier materials at low densities such as in the pellet filling around the silo.	SKB's assessment assumes that water flows through the silo remain more or less constant in the long term (after 1,000 years) because of the surrounding bentonite barrier. This is a key assumption on which the safety assessment depends.
Review of monitoring data on settlement, horizontal pressures and wetting of the bentonite surrounding the silo.	It is vital to see how well SKB's predictions for these parameters agree with the actually observed performance of the silo bentonite.
Review of SKB's justification for the proposed repository design and demonstration of optimisation.	Section 4 of SSMFS 2008:37 requires that '*Optimisation must be performed and the best available technique shall be taken into consideration in the disposal of spent nuclear fuel and nuclear waste*.'
Detailed review of the assumptions, data and models used to simulate the chemistry (e.g. redox state, speciation, solubility, sorption, precipitation) and transport of Mo, C-14, Pu and U.	Calculated potential doses due to radionuclide transport via the groundwater pathway are, in general, directly related to the solubilities of the radionuclides in the water, as affected by retardation processes such as sorption. The radionuclides identified are the key contributors to calculated potential doses in the main scenario and the less probable scenarios.

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Preparatory review of the integrity of reinforced and non-reinforced concrete structures in the extension of SFR

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Registration number: SSM2015-1038
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Abstract

The Center for Nuclear Waste Regulatory Analyses (CNWRA®) reviewers evaluated the information the Swedish Nuclear Fuel and Waste Management Company (SKB) provided on concrete integrity in the long-term safety assessment of the proposed SFR 3 repository for low- and intermediate-level radioactive waste. Specifically, the reviewers evaluated the information on SKB's proposed design and operations to closure (initial state) and post-closure safety assessment of the intermediate-level waste vault 2BMA, the four low-level waste vaults 2 to 5BLA, and the 1BRT vault for nine reactor pressure vessels (RPVs). SKB described the design of vaults, engineered barriers, waste forms, and waste packages for the three vault types. The description was thorough and sufficient to proceed with a more detailed evaluation in the Main Review Phase. However, as discussed in the Need for Complementary Information 4 (NCI 4) in Appendix 2, SKB did not provide information on the impact of falling rocks and the effect of the weight of accumulated rock debris on the International Organization for Standardization (ISO) containers and the mechanical effects on the waste packages that may influence the performance of 2 to 5BLA vaults. Also, as discussed in NCI 7, SKB did not provide a justification showing that seismic damage of 2 to 5BLA waste vaults would be insignificant, so the potential effects on the safety assessment also are negligible.

SKB did not provide references to evaluations of stress due to mechanical and chemical processes, and use of these stresses in the safety analysis of 2BMA and 1BRT vaults (NCI 6). SKB disregarded overburden weight and earthquake loading to assess the effects of mechanical processes on waste forms and packaging in the safety assessment for all six SFR 3 vaults, without providing a technical rationale (NCI 5).

SKB provided adequate general discussions of the mechanical and chemical degradation of the engineered barriers of SFR 3. SKB presented analytical models and numerical reactive transport models to investigate chemical processes that cause fractures and chemical degradation in concrete barriers, and the impact of fractures on post-closure performance of the SFR repository. However, SKB did not clearly identify specific mechanical and chemical processes for each reinforced and non-reinforced concrete structure or its components that are judged by the reviewers to be important in view of the safety assessment results (NCI 2). Additionally, SKB did not provide references describing how these processes were incorporated quantitatively in the safety assessment (NCI 3).

SKB identified the features, events, and processes (FEPs) for the SFR 3 site, with the exception of events related to major mishaps and accidents that may occur during the operational phase of the repository. It is suggested that SKB provide information on the identification of potential events and accidents and their likelihoods during the initial state and plans for mitigation when relevant to long-term safety assessments (NCI 1).

SKB described the concrete plugs that act as mechanical constraints for the hydraulically tight bentonite sections and also described plans for closing and sealing boreholes. The reviewers considered these descriptions to be thorough and with sufficient technical basis to proceed with the Main Review Phase.

The reviewers identified key topics of importance for SFR repository safety that may require detailed review effort and summarized those in Appendix 3 of this report. In-depth review of the documents relevant to these topics is recommended for evaluation of the initial conditions at the closure of the repository and implications for post-closure safety.

Contents

1. Introduction

This report documents results from an independent preparatory review by the CNWRA of the SKB information supporting the application for extension of the final repository for low- and intermediate-level waste at Forsmark (SFR). Specifically, the focus of the review is on the mechanical and chemical processes that affect reinforced and non-reinforced concrete structures used as waste containers and barriers and for sealing tunnels in the extension of the SFR repository. Table 2.1 below provides a summary of safety functions of extension vaults, waste containers, and barriers as presented by SKB (SKB TR-14-01, Table 5-3).

Table 2.1: Safety functions of extension vaults, waste containers, and barriers

Vaults	Waste containers and barriers	Safety functions
2BMA	Waste	Limited amount of radioactivity
	Cementitious materials in waste packages and concrete barriers	Good retention of radionuclides
	2BMA	Low flow in waste vaults
2 to 5BLA	Waste	Limited amount of radioactivity
BRT	Reactor pressure vessels	Good retention of radionuclides
	Waste	Limited amount of radioactivity

The CNWRA review was aimed at (i) identifying the most relevant parts of SKB's documentation, as well as safety relevance of the review area; (ii) suggesting the most important review topics for Swedish Radiation Safety Authority's (SSM) Main Review Phase, describing why these topics are judged to be important in view of the safety assessment results, and providing safety relevance for each topic and priority for review; (iii) assessing the adequacy of relevant models, data, safety functions, and uncertainties; (iv) identifying and stating merits and weaknesses of SKB's work; (v) suggesting needs for complementary information or clarifications that are deemed necessary to effectively assess the license application in depth; and (vi) assessing the overall quality of SKB's documentation (structure, transparency, traceability, scientific soundness, maturity of technical solutions, and methodology). The activities and results documented in this report are intended to support the SSM review and assessment activities of SKB's application for the extension of the SFR repository.

In conducting the review, the CNWRA reviewers paid attention to the integrity of the engineered structures that have containment or barrier functions, and on the processes of concrete and cement degradation that also can interfere with the functions of natural barriers. CNWRA staff review of the mechanical stability of structures included evaluation of potential effects of rock mass instability and earthquake loads. The effects of chemical degradation products and their amounts on reinforced and non-reinforced concrete were evaluated as part of the chemical process review. The review effort was limited to the extension of the SFR repository, referred to as SFR 3. This extension includes the 2BMA vault for intermediate-level waste, the 2 to 5BLA vaults for low-level waste, and the 1BRT vault for nine boiling water RPVs.

The report is organized as follows. Chapter 1 provides a summary of the CNWRA independent preparatory review and assessment. Chapter 2 provides the objectives and scope of the review. Chapter 3 is the central part of the report and includes a brief summary of the design, analysis, and assessments of SFR 3 by SKB and our preparatory review assessment. Chapter 4 is the consultant's general statement about the structure, transparency, traceability, scientific quality and soundness, and errors and omissions in SKB's application. Chapter 5 is the list of references. Appendix 1 includes a list of SKB documents evaluated in this report, Appendix 2 provides a list of suggested NCIs, and Appendix 3 is a list of suggested topics for SSM for review during the Main Review Phase.

2. Review and assessment of integrity of concrete structures in the proposed SFR extension

2.1. Brief summary of review and assessment

2.1.1. General

SKB designated its report "Safety Analysis for SFR Long-Term Safety: Main Report for the Safety Assessment SR-PSU" (SKB TR-14-01) to serve as the main component for the assessment of long-term safety of the SFR repository in Forsmark, Sweden. This SKB SR-PSU report (hereafter called Main Report) supports the SKB applications to SSM for a license to extend the SFR repository. The extended SFR repository includes two parts:

(i) existing facility, SFR 1

(ii) proposed extension, SFR 3

The SKB objective for post-closure safety is based on the principle of preventing, limiting, and delaying release of radionuclides from the repository. Two main safety functions in the long-term performance of SKB's near-field repository systems are low flow in waste vaults and retention of radionuclides in engineered barriers. The assessment of the response of waste form matrix and the engineered barrier systems to mechanical and chemical processes is based on the evaluation of

(i) the degradation of hydraulic properties that limit groundwater flow and

(ii) reduction of sorption capacity that limits the mobility of radionuclides. SKB implemented abstractions of processes to analyse scenarios that may lead to radionuclide release and radiological doses.

The Main Report (SKB TR-14-01) provides an overview of the purpose of demonstrating long-term (post-closure) safety of the extended SFR repository, and general prerequisites including regulations; bases for post-closure safety relying on preventing, limiting, and delaying release of radionuclides; and the 10-step safety assessment methodology. SKB concludes that the extended SFR repository meets regulatory criteria with respect to long-term safety. The body of the Main Report (SKB TR-14-01) and relevant cited references are reviewed next.

2.1.2. Safety assessment

In the safety assessment, SKB evaluated two periods: 1,000 years and 100,000 years after closure. For long-term evaluation, the first 50,000 years includes a period of temperate and periglacial climate, and SKB described the following 50,000 years as glacial and post-glacial conditions. SKB developed and analysed three categories of scenarios for long-term safety assessment, referred to as main, less probable, and residual. Shoreline displacement is the main driver for groundwater flow through the repository in both variants of the main scenarios—global warming and early periglacial climates. SKB evaluated mechanical and chemical processes in the main scenario with regard to degradation of concrete and cementitious materials in waste packages and the engineered barriers. SKB considered mechanical degradation of concrete to change the hydraulic properties affecting water flows inside the vaults, while chemical degradation was regarded to cause changes to the retention of radionuclides by sorption (thus, affecting radionuclide transport rates). Review and assessment of SKB information on mechanical and chemical degradation processes is discussed in Sections 3.1.5 and 3.1.6.

In less probable scenarios, SKB evaluated the safety function of low flow through the vault assuming accelerated degradation of concrete. In the less probable scenarios, SKB considered that degradation of bentonite and earthquakes affect only the SFR 1 structures. Under residual scenarios, SKB evaluated loss of barrier functions in the repository; for example, SKB considered no sorption or high water flow to establish the contribution of different barriers to the overall system performance.

Further to the scenario development and analysis, SKB calculated radiological dose consequences and estimated the probability of occurrences for each scenario. The probability of occurrences for global warming and early periglacial climates in the main scenarios was considered to be 1, but probabilities were estimated for less probable scenarios. SKB calculated risk using the scenario probability and radiological dose consequences. SKB also considered combinations of the scenarios in its analysis.

The term mechanical degradation refers to fracturing of the concrete and changes in pore structures caused by mechanical loading, degradation of reinforcement, gas formation, and leaching in the Main Report. SKB considered fracturing by freezing to occur under glacial and post-glacial conditions (SKB TR-14-01). SKB considers chemical degradation of concrete in waste form, waste package, and barriers is affected by factors, such as advection, dispersion, and diffusion of solutes in the groundwater and chemical interaction with those solutes; metal corrosion; gas formation and transport; and reactive transport of radionuclides, alteration products, and corrosion products.

It is not transparent how SKB evaluated the parameters for degradation and the temporal effects of each of the factors in the safety analysis. The SKB safety analysis results do not show the risk contribution of each of the factors in mechanical and chemical processes that may lead to radiological release in each analysed scenario. It is recommended that the reviews of mechanical and chemical processes be coordinated with the reviews of the safety and risk assessment to evaluate the importance of these factors to the overall risk.

2.1.3. Features, events, and processes

SKB discussed identification and screening of FEPs that are important to post-closure performance in Chapter 3 of the Main Report (SKB TR-14-01) and in a supporting document (SKB TR-14-07). SKB excluded events related to major mishaps and accidents that may occur during the operational phase of the repository (SKB TR-14-01, Table 3-1) from the initial state FEPs because SKB concluded that the probabilities of such events are low. However, this SKB conclusion is not supported by any reference to a related evaluation.

SKB stated that the events during the operational period will be known and mitigation measures can be taken based on the specific events. Therefore, it is recommended that SKB provide information (NCI, Appendix 2) on the identification of potential events and accidents and their likelihoods during the initial state, as well as plans for mitigation when relevant.

In addition, SKB should discuss the experiences with operational events, if any, or relevant deviations from the initial-state assumptions in SFR 1 during the operational period. SKB should explain how relevant experiences are addressed in the design and effects of deviations in initial-state assumptions on long-term performance of the barrier systems of SFR 3.

2.1.4. Description of vaults and safety functions

The SFR 3 repository vault system consists of six long parallel rock caverns with four BLA vaults located in the middle and the 2BMA and 1BRT vaults on either side of the BLA vaults. The vaults will be constructed 120 m below sea level. These vaults are 15 to 18 m wide, 13 to 16 m high, and 240 to 275 m long (SKB TR-14-01, SKB TR-14-02)). The vault and barrier systems are depicted elsewhere (in SKB TR-14-02, Figures 5-2 and 5-3 for 2BMA; Figures 9-2 and 9-3 for 2 to 5BLA; and Figures 10-2 and 10-3 for 1BRT). The rock walls and roof will be lined with shotcrete. The barriers and safety functions for the SFR 3 repository vaults are listed in Table 2.1 of this report and discussed in this section.

The 2BMA system will contain 14 free-standing, 8 m-high unreinforced concrete caissons, founded on crushed rock, and levelled with gravel. The waste packages consisting of steel and concrete moulds will be placed in the caissons using a remote-controlled overhead crane, and the caissons will be filled with grout.

The proposed 1BRT vault will contain nine RPVs to be placed end-to-end and installed on the concrete floor (SKB TR-14-02, Figure 10-1). The RPVs will be filled with concrete or cementitious grout and then embedded in grout.

The 2BMA and 1BRT vaults will be backfilled with macadam (crushed rock). The 2 to 5BLA vaults will contain ISO containers stacked vertically within the longitudinal walls of the vault. The vault has a concrete floor on top of a draining foundation. The ISO containers are made of carbon steel and the waste inside the containers will be packed in boxes, bales, and drums or directly emplaced. The 2 to 5BLA vaults are not planned to be backfilled, but both ends of the vault where it connects to the tunnels will be backfilled with macadam and concrete (SKB TR-14-02, Figure 9-3). The Main Report provided brief descriptions of closure plans for the SFR 3 vaults, with details discussed in the closure plan report (SKB Document 1358612).

Two plug sections, P2TT and P2BST (SKB TR-14-01, Figure 4-27), are to be installed to seal the waste vaults in SFR 3. Individual plug systems for 2BMA, 2 to 5BLA, and 1BRT are depicted in Figures 4-10, 4-23, and 4-26 of the Main Report. In general, all plug systems consist of a hydraulically tight bentonite section and a concrete plug to act as a mechanical constraint for the bentonite section. Mechanical stresses can develop in the concrete plugs because of the swelling pressure of the bentonite material, but concrete plugs are designed to withstand the bentonite swelling pressure (SKB TR-14-01).

The Main Report stated that SKB has conducted tests and experiments for the behaviour, fabrication, and installation of plugs for long-term safety; these were discussed in a laboratory report (SKB TR-13-10). SKB stated that the designs of plugs presented in the license application constitute solutions that are technically feasible but plug designs can be developed further and optimized before the closure of the SFR repository (SKB TR-14-02, Section 11.2). SKB studied and developed concepts of borehole sealing in SKB R-07-58, which provided the main principles for sealing of boreholes and experimental and test results that were used in SKB TR-14-02.

The engineered barriers discussed in SKB TR-14-04 are reviewed in Section 3.1.5. The engineered barriers in 2BMA are waste package (consisting of waste, drums and moulds) and concrete walls. The primary barrier in 1BRT is the slow corrosion of the waste ensured by the concrete cover surrounding the waste. 2BMA and 1BRT have a macadam or sand backfill. The engineered barriers for BLA are not credited to perform any safety functions. For each of the vault systems, SKB discussed design considerations and expected functions for the barrier systems and components that are relied on for post-closure safety (SKB TR-14-02). In addition, SKB discussed the expected mechanical and chemical conditions of waste form, waste form packaging, and barrier systems at repository closure (i.e. initial state).

CNWRA reviewed the information in the Initial State Report (SKB TR-14-02) and found that SKB discussed, in sufficient detail, the reference design of the repository and the barrier components. The description of the reference design, including citations of supporting references, was thorough and sufficient to proceed with a more detailed evaluation in the Main Review Phase.

In evaluating the post-closure repository safety effects of the initial-state mechanical integrity and stability of the waste and barriers, SKB stated that the depth of the rock surrounding the SFR 3 waste vaults 2BMA, 2 to 5BLA, and 1BRT (SKB TR-14-02, Sections 5.2, 9.2, and 10.2) results in favourable conditions with respect to mechanical stability of these vaults. In Section 6.3.3 of the Main Report, SKB briefly discussed the long-term stability of vaults and referred to a report (SKB R-13-53) for the determination of the long-term stability of the BMA and BLA vaults. CNWRA did not evaluate the report SKB R-13-53 in detail. It is recommended that a more detailed assessment of information in this report be conducted in the Main Review Phase.

2.1.5. Waste form, waste packaging, and engineered barrier in SFR 3

Mechanical and chemical degradation of the structural integrity of the waste form and steel and concrete waste packaging is discussed in the Waste Form and Packaging Process Report (SKB TR-14-03, Chapters 3 and 4). In addition, the mechanical and chemical processes affecting barriers in 2BMA, 2 to 5BLA, and 1BRT vaults are discussed in the Engineered Barrier Process Report (SKB TR-14-04, Sections 5.3, 5.4, 8.3, 8.4, 9.3 and 9.4). SKB discussed the materials present in the SFR repository in the Main Report and data report (SKB TR-14-10). Cementitious materials are used in the 2BMA, 2 to 5BLA, and 1BRT vaults (SKB TR-14-01, Sections 4.3.2, 4.3.6, and 4.3.7; and SKB TR-14-10, Chapter 7). Structural concrete is used in the floor, walls, lid, and waste packages in the 2BMA vault; the floor and longitudinal walls in the 2 to 5BLA vault; and the floor in the 1BRT vault. Concrete grout is used as backfill around the waste packages in the 2BMA vault and embedment of RPVs. Cement mortar and grout are used as conditioning and solidification materials for the waste inside waste packages. SKB described the mixing proportions of the different concrete types present in the SFR repository (SKB TR-14-10, Table 7-1).

Mechanical Processes

Waste forms in SFR 3 include non-stabilized waste (emplaced in the 2 to 5BLA and 1BRT vaults) and stabilized waste (emplaced in the 2BMA vault). Mechanical processes may result in loss of structural integrity by waste matrix fracturing, which SKB TR-14-03, Section 3.4, stated can be caused by

(i) mechanical stress (structural fractures) from applied loading, rockfall, seismic ground motion, or foundation shifting

(ii) volume changes (intrinsic fractures) from shrinkage during drying, thermal expansion/contraction, creep, and chemical degradation (e.g., alkali-aggregate reaction and rebar corrosion)

Since 2BMA vaults will not contain bituminized waste, fractures associated with swelling pressure from bituminized waste is not a concern. Fracture formation and propagation may compromise the structural integrity, causing an increase of water flow and enhancing radionuclide transport through the waste form and packaging and radionuclide release rates.

In the Waste Form and Packaging Process Report (SKB TR-14-03), the fracturing of waste matrix is handled by choosing modified values for the hydraulic conductivity and diffusivity in the hydrological, concrete degradation, and radionuclide transport models.

Mechanical fracturing of concrete packaging can be caused by volume expansion of reinforcing steel and cement-encapsulated waste (SKB TR-14-03, Section 4.3). Steel packaging is not credited as a barrier, but volume changes of steel in waste form and mechanical loads will challenge the structural integrity and cause fracturing. Mechanical processes affecting the barrier functions of 2BMA, 2 to 5BLA, and 1BRT vaults are discussed in Sections 5.3, 8.3, and 9.3 of the barrier process report (SKB TR-14-04). The engineered barrier in 2BMA and 1BRT consists of concrete or grout and macadam or sand backfill. The concrete is a hydraulic barrier for transport of radionuclides under saturated conditions.

The water flow is expected to vary with time and increase as barriers degrade. Hydraulic properties and uncertainties associated with degraded concrete are input to the performance assessment model.

In the 2BMA and 1BRT vaults, the phenomena that contribute to mechanical degradation include factors, such as stress caused by weight, hydraulic stresses, creep deformation, corrosion of reinforcement, and freezing. Additional discussion on the mechanical degradation of concrete barriers is provided by SKB in a separate report (SKB R-13-40, Section 4.2). The spaces between the ISO containers and the rock in the 2 to 5BLA vaults are not filled with engineered backfill; thus, SKB did not identify any degradation issues related to barriers.

CNWRA reviewed the information on the mechanical processes in the waste form, waste form packaging, and engineered barrier systems and finds that SKB provided information that was not fully transparent to the reviewers. This lack of clarity or incomplete information is explained in the following paragraphs.

Mechanical processes in the waste form matrix were discussed in Section 3.4 of the waste form and packaging process report (SKB, TR-14-03). SKB stated that fracturing is addressed by selecting appropriate hydraulic conductivity and diffusivity values in the hydrogeological, concrete degradation, and radionuclide transport models. However, this statement is not supported by references explaining how fracturing by mechanical processes is quantified by changes in hydraulic conductivity with time, including evaluation and propagation of uncertainties, to evaluate effects on the timing and extent of radionuclide releases. It is recommended that SKB describe how fracturing of waste form and relevant mechanical processes discussed in the Waste Form and Packaging Process Report (SKB TR-14-03) and Engineered Barrier Process Report (SKB TR-14-04) are accounted for in the safety analysis (NCI 4 and NCI 7, Appendix 2).

The SKB discussion of mechanical processes affecting waste form and steel and concrete packaging in Section 3.4 of the Waste Form and Packaging Process Report (SKB TR-14-03) does not appear to include consideration of stress induced by:

(i) relevant overburden weight of the grout, backfill material, and potential closure from rock deformation or rockfall

(ii) dynamic loading from seismic events

The forces from the mentioned loading may compromise the structural integrity of the waste form and waste packaging by forming cracks and fractures, thus developing pathways for radionuclide release and for groundwater flow through the containment structures. Stress-induced fractures by mechanical loading on concrete barriers are similar in the 2BMA and 1BRT vaults. Fractures may accelerate the degradation of the vaults and influence the timing and extent of radionuclide release.

It is recommended that SKB provide a rationale for excluding the effects of overburden weight and earthquake loading in the evaluation of properties of the waste form, waste form packaging, and concrete barriers as related to flow and radionuclide transport modelling, or provide references in which fracturing from mechanical processes is addressed in the context of post-closure safety analysis (NCI 6, Appendix 2).

SKB discussed mechanical effects of rockfall on the 2 to 5BLA waste vaults in Section 8.3 of the Engineered Barrier Process Report (SKB TR-14-04). SKB concluded rockfall from the roof and walls on the waste package after degradation of shotcrete is not expected to influence the performance of the BLA vaults because it does not affect water flow through the rooms. Section 6.3.3 of the Main Report discussed a numerical study of the rockfall and caving process (SKB R-13-53), which determined that the loosened rock blocks may fill the empty space in the vault.

It is recommended that SKB provide a justification that rockfall impact and the weight of accumulated rock blocks will not compromise the structural integrity of the ISO containers and waste packages in 2 to 5BLA waste vaults and that those processes are not likely to affect the timing and extent of radionuclide release from BLA vaults (NCI 5, Appendix 2).

SKB did not discuss the effects of seismicity on unbackfilled 2 to 5BLA waste vaults. The ISO containers in 2 to 5BLA waste vaults are stacked (six containers, assuming half-height containers) up to a height of 9.0 m, as shown in SKB (SKB TR-14-01, Figure 4-22). Seismic ground motion may induce sliding and overturning of free standing containers. Potential kinematic instabilities may result in collisions, impacts, and drops leading to loss of integrity of the containers and the waste packages.

It is recommended that SKB provide a rationale for not evaluating an earthquake scenario in the safety assessment related to long-term performance of the 2 to 5BLA waste vaults (NCI 8, Appendix 2).

It is noted that the mechanical stability and integrity of the waste form and barrier systems are not supported by technical evaluation and relevant models (e.g. NCIs 5, 6, and 8 request information related to mechanical evaluations, Appendix 2). For example, although SKB does not assign credit to metallic containers (as they are assumed to corrode following repository closure), implicit in the SKB evaluation is the assumption that barriers maintain their geometrical shape. Therefore, SKB implicitly assumes that the metallic containers provide structural support so that waste forms will not be fractured.

Additional evaluation by SKB would help establish whether preserving the geometry of the waste form is relevant to the long-term safety assessment. In an alternative scenario, waste forms could potentially be fractured more readily, releasing embedded radionuclides to the environment. An assessment is needed on whether such an alternative scenario is feasible or influential on radionuclide release and dose estimates.

Chemical Processes

According to the Main Report, the SFR 3 design contains:

(i) steel waste packages

(ii) ISO waste packages

(iii) scrap metals

(iv) reinforced concrete waste packages

(v) concrete floors, walls, and lids

(vi) cement mortar and grout

(vii) shotcrete

(viii) concrete plugs

Carbon and stainless steel are present in various scrap metals and waste packages. In Section 6.3.7 of the Main Report, SKB provided a general discussion of the chemical evolution of the waste domain. SKB discussed the degradation and longevity of the SFR 3 engineered barriers, as they are affected by chemical interactions when the components of the barriers come in contact with groundwater and waste. SKB stated that the chemical evolution of the barriers also is important for sorption and for the release of radionuclides and other species. Leaching and formation of secondary phases can cause porosity changes and fracturing, and gas build-up can cause fracturing of the engineered barrier components, which in turn would affect radionuclide transport. Corrosion products of steel in waste packages can cause volume increase and fracture the concrete; on the other hand, radionuclides may readily sorb onto corrosion products. Ettringite formation in pores could cause fracturing of concrete packaging and cement matrices.

SKB presented analytical models and numerical reactive transport models to investigate chemical degradation of concrete barriers and the impact of fractures on the post-closure performance of the SFR repository (SKB R-13-40). Fractures may affect key parameters—such as hydraulic conductivity, effective diffusivity, and sorption capability—that are used in groundwater flow modelling and radionuclide transport modelling for the SFR repository. SKB stated that since many waste types in SFR are stabilized in concrete or cement, the results presented in SKB (SKB R-13-40) also may be relevant to metal waste and waste packages in the SFR repository.

SKB provided metallic corrosion data, concrete/cement sorption data, rock matrix and crushed rock sorption data, concrete/cement diffusivity data, and concrete/cement hydraulic data in the Data Report for the SR-PSU safety assessment (SKB TR-14-10). Corrosion rates for carbon and stainless steel were used to compute redox states, to quantify gas generation in the repository, and to evaluate the release of radionuclides from metal waste. It appears to the CNWRA reviewers that, as in a previous safety assessment for the presently operated SFR 1, the steel in waste packaging is assumed to be completely saturated by water after the repository is sealed and the steel is assumed to corrode instantaneously after repository closure. In other words, the steel in waste packaging was not credited as a barrier to limit radionuclide transport (SKB TR-14-09).

SKB provided general discussions of the mechanical evolution of the geosphere and chemical evolution of the waste domain, respectively, in Sections 6.3.3 and 6.3.7 of the Main Report. However, SKB did not clearly and specifically identify mechanical and chemical processes—such as earthquake load, leaching of concrete, and freezing—that may affect the long-term performance of the specific reinforced and non-reinforced concrete structures and other engineered systems, such as steel waste packages, caisson concrete walls, reinforced concrete waste packages, and cement grouting. These structures and systems are judged to be important in view of the safety assessment results. It is recommended that SKB clearly identify the mechanical and chemical processes for each reinforced and non-reinforced concrete structure and other engineered systems that SKB relied on in its safety assessment (NCI 2, Appendix 2). It is not clear which mechanical and chemical processes SKB considered in the safety assessment, and which of those processes are influential to radionuclide release and radiological dose assessments.

2.1.6. Relevant models, data, safety functions, and handling of uncertainties

Post-closure safety functions to ensure long-term performance of (i) hydraulic barriers to constrain water flow and (ii) chemical barriers to retard release from waste materials and engineered barrier systems were adequately presented by SKB in the SR-PSU Main Report (SKB TR-14-01) and supporting documents. SKB systematically identified factors that would affect radionuclide releases to the environment and evaluated each of those factors. SKB adopted well-accepted analytical models for chemical processes. However, evaluations of the mechanical stability and integrity of the waste form and barrier systems do not appear to be supported by technical evaluation and relevant model analysis (e.g., NCIs 4, 5, and 7 request information related to mechanical evaluations).

SKB described the design functions of the near-field repository system adequately to support the long-term safety goals (SKB TR-14-02).

SKB described the data used for post-closure performance analysis in the Data Report and Input Data Report (SKB TR-14-10 and TR-14-12). SKB discussed uncertainties of mechanical and chemical processes in the Main Report and in the Waste Form and Packaging Process Report (SKB TR-14-03), the Engineered Barrier Process Report (SKB TR-14-04), and the Data Report (SKB TR-14-10). SKB also discussed spatial and temporal variability of data in the Data Report (SKB TR-14-10). These reports provide a qualitative discussion of uncertainty and variability; however, the approach SKB adopted to quantify uncertainties and propagate those uncertainties into the safety analysis is not transparent.

Based on the preparatory review of SKB (TR-14-03 and TR-14-04), it appears the data for mechanical and chemical processes were evaluated deterministically (SKB TR-14-01, Section 11.4.7), while for the radionuclide transport model and dose calculations, data uncertainties were quantified probabilistically. As part of the Main Review Phase, it is recommended to evaluate the extent of conservatisms applied to abstractions of mechanical and chemical effects, and assess the sensitivity of relevant parameters of those abstractions to radionuclide release and radiological dose consequences.

3. The consultants' general statement about the structure, transparency, traceability, scientific quality and soundness, and errors and omissions in SKB's application

3.1.1. Structure

The Main Report (SKB TR-14-01) serves the function of the central document of the license application for the extended SFR repository, with cited references supporting the summarized conclusions. The Main Report frames the SKB-evaluated technical areas and related regulatory areas in the context of the safety analysis. The structure of each reference report varies depending on the technical content, its purpose, and its relationship to other reports, including the Main Report and the safety analysis report.

In order to assess the safety of the repository, SKB defined the repository system as the repository and its environs and considered the future evolution of the repository system. In the Main Report (SKB TR-14-01) SKB described a 10-step Safety Assessment methodology. SKB stated that this methodology is based on SKB's most recent safety assessment for SFR (SKB R-08-130) and is reasonably consistent with the safety assessment in SKB's application for licensing of a Spent Fuel Repository (SKB TR-11-01). This 10-step Safety Assessment methodology includes common essential elements of international safety assessments such as FEPs, definition of initial state at repository closure, repository external conditions and internal processes and their evolution, identification of safety functions, and formation of scenarios. Relevant input data for each step properly points to supporting SKB reports. Based on this 10-step methodology, consistency with SKB R-08-130 and SKB TR-11-01, and CNWRA experience with post-closure safety assessment of spent fuel disposal repositories, the structure of SKB's Safety Analysis is deemed adequate to support demonstration of safety with respect to degradation of concrete barriers and waste packages (provided SKB addresses NCI 1 through NCI 7).

3.1.2. Transparency and traceability

In general, the CNWRA reviewers had ready access to information and were able to identify documents in which key analyses were reported. The analyses were logical and the conclusions were well supported. There were a number of areas in which key analyses were either non-existent or the references were lacking. These areas are identified in Appendix 2 of this report, expressed as suggested NCIs. In general, the information presented in the main report and summarized conclusions, depending on analyses documented elsewhere, are traceable to cited references. However, there are instances of unsupported statements and conclusions by SKB, as noted in Appendix 2 of this report. It is recommended that SSM requests SKB to provide missing references or develop the needed technical bases.

3.1.3. Scientific quality and soundness

The reference documents provide information consistent with state-of-the-art scientific and engineering methods and site-specific technical data that support the safety analysis of the SFR repository. The quantitative consideration in the safety analysis of the impact of long-term degradation of concrete, steel, and waste form matrix on the SFR barrier functions is an important merit of the SKB work. The work SKB performed took advantage of experience gained from the analysis of 1BMA to implement the new 2BMA design, clearly improving the design.

3.1.4. Errors and omissions

Potential omissions with regard to references supporting conclusions of the main report are identified, in the form of potential NCIs, in Appendix 2. No other significant omission was identified within the scope of this preparatory review. Within the context of the preparatory review, which did not incorporate detailed review of technical analyses, no significant errors were encountered.

3.1.5. Suitability of the layout

The layout of the SFR 3 repository vault system consists of six long parallel caverns excavated in rock as shown in Figure 4-4 (SKB TR-14-01). The vault system consists of four BLA vaults located in the middle and the 2BMA and 1BRT vaults on either side of the BLA vaults. The 2BMA vault, which is 20-m wide, 16-m high, and 275-m long, will be backfilled after placement of waste. The 1BRT vault, which also will be backfilled, is 15-m wide, 13-m high, and 240-m long. The 2 to 5 BLA vaults are 18-m wide, 14-m high, and 275-m long. These vaults will not be backfilled. The vaults are assumed to be separated by 19.5-m thick rock pillars, based on the report SKB R-13-53. The layout of SFR 1 vaults in comparison consists of four parallel vaults with three vaults (one BMA and one to two BTF) backfilled and only one BLA vault that is not backfilled. The SFR 1 also consists of a 70 deep and 30 m diameter silo vault. SKB evaluated the long term stability of the vaults in SFR 1 by three-dimensional discontinuum modelling (SKB R-13-53). SKB considered BLA and BMA vaults in the analysis and evaluated the potential instability of cavern roof and walls under degraded conditions of rock mass. The width of BLA vaults in SFR 3 is wider by 3 m and height is higher by 2 m than the SFR 1 design. The lengths of both vaults in SFR 1 also are smaller than SFR 3. These changes in dimensions may not have a significant effect on the overall conclusions in the long term stability report (SKB R-13-53). Detailed review of the long term stability document (SKB R-13-53) is beyond the scope of this report; however, the approach used, geometry of excavations, *in-situ* stress state, fracture disposition, and rock and fracture properties can be applied and similar conclusions can be assumed for the SFR 3 vaults for the purpose of assessing suitability of the layout. It can be concluded that the SFR 3 layout may not have adverse long term effects on mechanical and chemical degradation of waste and barriers. SKB did not propose a silo in SFR 3 layout, thus suitability of silo construction was not evaluated.

3.1.6. Design and verification techniques

SKB provided a discussion of the design of SFR 3 vaults and engineered barriers in the Initial State Report (SKB TR-14-02). SKB used standard designed components such as ISO containers and provided references to design drawings and reports. It is recommended that a detailed review of these design drawings and reports be conducted in the Main Review Phase. However, based on the discussion of the reference design, including citation of supporting references, use of standard design components, and our knowledge and experience on design of nuclear facilities, we deem SKB design and verification techniques to follow industry standards.

3.1.7. Demonstration of the feasibility of the construction

A brief description of SFR 3 vaults and the engineered barriers has been provided in Section 3.1.4 of this report. The SFR 3 repository vault system consists of six long parallel rock caverns with four BLA vaults located in the middle and the 2BMA and 1BRT vaults on either side of the BLA vaults. The rock walls and roof will be lined with shotcrete. Based on the discussions provided in Sections 3.1.4 and 4.1.5 of this report and our knowledge of underground excavation of rocks, it is reasonable to state that suitable excavation methods exist for the construction of SFR 3 vaults and it can be concluded that it is feasible to construct SFR 3 vaults at Forsmark and line their rock walls and roof with shotcrete.

The 14 free-standing, 8 m-high unreinforced concrete caissons of 2BMA will be founded on crushed rock and levelled with gravel. The waste packages consisting of steel and concrete moulds will be placed in these caissons using a remote-controlled overhead crane, and the caissons will be filled with grout. The nine RPVs in the 1BRT vault will be placed end-to-end and installed on the concrete floor. The RPVs will be filled with concrete or cementitious grout and then embedded in grout. The 2BMA and 1BRT vaults will be backfilled with macadam (crushed rock). The ISO containers of 2 to 5 BLA vaults will be stacked vertically within the longitudinal walls of the vault. The vault has a concrete floor on top of a draining foundation. The ISO containers are made of carbon steel and the waste inside the containers will be packed in boxes, bales, and drums or directly emplaced. The 2 to 5BLA vaults will not be backfilled. Based on our knowledge and experience of construction inspection of various nuclear facilities, it is reasonable to conclude that technology is readily available to construct the engineered systems, as described herein for 2BMA, 1BRT, and 2 to 5 BLA systems.

The Main Report provided brief descriptions of closure plans for the SFR 3 vaults, with details discussed in the closure plan report (SKB Document 1358612). Both ends of the SFR 3 vaults where they connect to the tunnels will be backfilled with macadam and concrete. The SFR 3 vaults will be sealed by installing two plug sections, P2TT and P2BST (SKB TR-14-01, Figure 4-27). Individual plug systems consisting of a hydraulically tight bentonite section and a concrete plug to act as a mechanical constraint for the bentonite section for 2BMA, 2 to 5BLA, and 1BRT are depicted in Figures 4-10, 4-23, and 4-26 of the Main Report. It is reasonable to state that technology exists to construct the closure systems as discussed herein.

3.1.8. Choice of technical solutions

Based on our assessment of the layout, design, and feasibility of construction of the SKB proposed SFR 3 vaults, waste containers, and barriers, we conclude that SKB used an appropriate approach for designs at Forsmark. SKB made use of its experience gained from the analysis of 1BMA to implement the improved 2BMA design (e.g., use of non-reinforced concrete structures instead of reinforced concrete structures). It is recommended that an identification of improvements to the design of SFR 3 compared to the SKB proposed design in the application be conducted in the Main Review Phase.

3.1.9. SKB seismic analysis of SFR 1 silo concrete structure

In Section 7.6.5 of the Main Report (SKB TR-14-01), SKB stated that the earthquake scenario for the SFR repository is based on the assumption that the safety function “low flow in waste vaults” deviates from the main scenario for the safety assessment because SKB could not rule out damage of barriers by earthquakes. SKB also stated that the SFR 1 safety assessment (SKB R-08-130) showed that the radiological effects caused by a damaged BMA structure were small, and SKB conducted a seismic analysis only for the SFR 1 silo concrete structure (SKB R-13-52). Although the results of the seismic analysis of the SFR 1 silo concrete structure cannot be directly used for predicting the seismic response of SFR 3 engineered barriers, at the request of SSM the CNWRA reviewed the SKB seismic analysis of the SFR 1 silo (SKB R-13-52) to assess the approach and methodology used, assumptions and idealizations made to model the system, use of site and system specific data, consideration of interactions between the engineered and natural systems, and related parameters and considerations.

SKB used the finite element computer code ADINA (SKB TR-14-11) to conduct the seismic analysis of the SFR 1 silo concrete structure. The seismic response spectrum analysis was conducted for earthquake loads with annual exceeding frequencies of 10^{-5}, 10^{-6}, and 10^{-7}, derived for use in the nuclear power industry in Sweden (SKI Technical Report 92:3). The seismic loads at the ground surface corresponding to the exceeding frequencies were conservatively used in this analysis. Other loads considered were the dead weight of the structure, waste, and surrounding bentonite located between the Silo structure and the host rock. The long-term effect of creep and shrinkage on the concrete was also considered. This analysis did not consider the swelling pressure from the surrounding bentonite, temperature loads, and water pressure.

The possible deterioration of the concrete material was not considered in this analysis. The reinforcement was assumed to be severely corroded and therefore ineffective. The loss of concrete cover caused by corrosion of the reinforcement was taken into account.

The analysis modeled the silo concrete structure using the facility-specific dimensions and materials from appropriate existing drawings and design documents. This analysis used guidelines provided in the American Society of Civil Engineers (ASCE) 4-98 standard for selecting parameters such as material damping and choice of analysis method such as the response spectrum method of seismic analysis.

SKB assessed the capacity of the SFR 1 silo concrete structure to withstand the seismic load from the point of view of global stability of the structure of the silo, maximum stresses in the concrete material, and forces at the joint between the outer wall and the foundation slab. The seismic analysis results showed that the silo concrete structure will maintain its integrity for an earthquake with an annual exceeding frequency of 10^{-5}, but not 10^{-6}.

Based on our review of the SKB seismic analysis of the SFR 1 Silo concrete structure (SKB R-13-52), as briefly discussed above, it is concluded that SKB’s selection of seismic ground motion, seismic analysis method, and seismic analysis material parameters, such as damping, are based on national and international codes and standards. The modeling assumptions and idealizations made by SKB, including modelling of bentonite surrounding the silo and calculation of mass are consistent with industry practice. SKB adequately accounted for the degradation of the reinforced concrete structure by not taking any credit in the seismic analysis for reinforcing steel and concrete cover. The silo seismic analysis that SKB has conducted is of good technical quality and SKB has demonstrated its capability to perform seismic analyses of complicated nuclear facility concrete structures located underground at the SFR repository at Forsmark.

4. References

SKI Technical Report 92:3, Characterization of seismic ground motions for probabilistic safety analyses of nuclear facilities in Sweden, Summary Report, April 1992.

ASCE 4-98, Seismic analysis of safety-related nuclear structures and commentary, 2000.

APPENDIX 1

Coverage of SKB reports

Following reports have been covered in the review.

Table A-1: List of reports consulted and evaluated in the task

Reviewed report	Reviewed sections	Comments
TR-14-01: Safety analysis for SFR, long-term safety: main report for the safety assessment SR-PSU	Summary, 2.1, 2.2, 2.4, 2.6, 3.2, 4.1, 4.3, 4.7.2, 4.8, 4.2, 6.3.3, 7.4, 7.5,7.6, 7.7, 7.8, 7.9, 8, and 11	
TR-14-02: Initial state report for the safety assessment SR-PSU	2, 3.1, 3.2, 3.6, 3.7, 5, 9, 10, and 11	
TR-14-03: Waste form and packaging process report for the safety assessment SR-PSU	3.4, and 4.3	
TR-14-04: Engineered barrier process report for the safety assessment SR-PSU	3.2, 3.4, 5.1, 5.2, 5.3, 5.5, 8.3, 8.4, 9.3, and 9.4	
TR-14-07: FEP report for the safety assessment SR-PSU	2, 4, and 5 Appendices 5, 6, 9, 10, 11	
TR-14-09: Radionuclide transport and dose calculations for the safety assessment SR-PSU	24, 26, 39-52, and 57-58	
TR-14-10: Data report for the safety Assessment SR-PSU	2, 7, 9, 10, and 11	
TR-14-11: Model summary report for the safety assessment SR-PSU	3.1, 3.2, and 3.5	
TR-14-12: Input data report for the safety assessment	2 and 3	
TR-13-10: Aspo Hard Rock Laboratory, Annual Report 2012	–	
R-13-40: The impact of concrete degradation on the BMA barrier functions	Summary, 2, 4.1, and 4.2	

Reviewed report	Reviewed sections	Comments
R-13-52: A seismic evaluation of SFR. Analysis of the Silo structure for earthquake load	Abstract, 7-51, and 76-151	
R-13-53: Long term stability of rock caverns BMA and BLA of SFR, Forsmark	7-10, 12-13, 16-20, and 41-47	
TR-11-01: Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site Project	–	
R-08-130: Safety Analysis SFR 1, Long-term safety	4.5, 7.6.1, 8.4.3, and 10.3.1	
R-07-58: Borehole project-Final report of Phase 3	–	
Allmän del 1 kapitel 5, SFR förslutningsplan, SKB DokumentID 1358612 (in Swedish)	The illustrations	

APPENDIX 2

Suggested needs for complementary information from SKB

Complementary information is deemed necessary for in-depth and effective assessment of technical analyses supporting the license application. Each recommended need for complementary information (NCI) is presented here with respect to the relevant chapter of the Main Report.

1. SKB TR-14-01, Chapter 3, Handling of features, events and processes

   Provide an analysis and planned mitigation measures for the features, events and processes (FEPs) that may occur during the operational period of the extended SFR repository, and which could have long-term implications for radiological consequences. Swedish Nuclear Fuel and Waste Management Company (SKB) excluded events related to major mishaps and accidents that may occur during the operational phase of the repository (SKB TR-14-01, Table 3-1) because SKB considered the probabilities of such events to be low. SKB concluded that the events, if they occur during the operational period, will be mitigated based on the event type. However, SKB did not identify the events nor discuss mitigation measures. It is recommended that SKB provide (i) an analysis of FEPs identifying the relevant events and their likelihoods and a description of planned mitigation measures, and (ii) discussions on experiences with operational events, if any, or deviations from the initial state assumptions in SFR 1 observed during the operational period and how such experience is incorporated in the design and long-term performance analysis of the SFR 3 barrier systems.

2. SKB TR-14-01, Chapter 6, Reference evolution - Processes

   Clearly identify the mechanical and chemical processes (e.g., earthquake load, leaching of concrete, and freezing) that are judged to be important to the safety assessment results for (i) each reinforced and non-reinforced concrete structure and (ii) other engineered systems such as steel moulds, caisson concrete walls, reinforced concrete moulds used as waste containers and barriers, cement grouting, and borehole sealing. For example, Sections 6.3.3 and 6.3.7 of the Main Report (SKB TR-14-01) discussed the mechanical evolution of the geosphere and chemical evolution of the waste domain, respectively. However, SKB did not identify the specific mechanical and chemical processes that affect the long-term performance of the specific reinforced and non-reinforced concrete structures and other engineered systems that are judged to be important to the safety assessment results. Obtaining this information is important as it will allow a more focused review of significant processes during the detailed review phase.

3. SKB TR-14-01, Chapter 6, Reference evolution - Safety assessment

   Provide references that explain how processes were incorporated quantitatively in the safety assessment. For example, a mechanical process in the waste form matrix is discussed in Section 3.4 of the waste form and packaging process report (SKB TR-14-03), in which SKB states that fracturing is handled by choosing appropriate hydraulic conductivity and diffusivity values in the hydrogeological, concrete degradation, and radionuclide transport models. However, this statement is not supported by references that would allow verification, for example, of adopted values of the hydraulic conductivity and its uncertainty. This shortcoming in the SKB documentation applies to all relevant processes discussed in the waste form and packaging process report (SKB TR-14-03) and the engineered barrier process report (SKB TR-14-04.

4. SKB TR-14-01, Chapter 6, Reference evolution - Falling rock

   Provide information on the impact of falling rock and the effect of the weight of accumulated rock on the International Organization for Standardization (ISO) containers and mechanical effects on the waste packages that may influence the performance of 2 to 5BLA vaults pertinent to the safety assessment. Section 8.3 of the Engineered Barrier Process Report (SKB TR-14-04) discussed mechanical processes from rockfall in 2 to 5BLA waste vaults. Although rock blocks can fall from the roof and wall on a waste package after degradation of shotcrete, SKB concluded this rockfall would not be relevant to safety assessments as it would not affect water flow through the rooms. Section 6.3.3 of the main report (SKB TR-14-01) discussed a numerical study of the rockfall and caving process which determined that the loosened rock blocks may fill the empty space in the vault. An evaluation is needed of the potential safety and performance impacts of rockfalls and the overburden weight of rock blocks from caving in the 2 to 5BLA vaults.

5. SKB TR-14-01, Chapter 6, Reference evolution - Loads from grout, rock and earthquakes

   Provide a rationale for excluding overburden weight and earthquake loading in assessing the effects of mechanical processes on waste forms and packaging (SKB TR-14-03, Section 3.4). The SKB discussion of mechanical processes affecting waste forms and steel and concrete packaging in Section 3.4 of the Waste Form and Packaging Process Report (SKB TR-14-03) does not include consideration of stress induced by (i) relevant overburden weight of the grout, backfill material, and potential closure from rock deformation or rockfall and (ii) dynamic loading from seismic events. The forces of those static and dynamic loads may compromise the structural integrity of the waste packaging by forming cracks and fractures, which also could become pathways for groundwater flow. These cracks and fractures may accelerate the time frame of the waste form and packaging degradation processes. A rationale is needed for excluding in the safety analysis the effects of overburden weight and earthquake loading on waste forms and packaging (SKB TR-14-03).

6. SKB TR-14-01, Chapter 6, Reference evolution - Stresses

   Provide references documenting stress evaluations due to mechanical and chemical processes and consideration of these stresses in the safety analysis (SKB TR-14-04, Sections 5.3 and 9.3). Sections 5.3 and 9.3 of the Engineered Barrier Process Report (SKB TR-14-04) discuss mechanical and chemical processes that can affect the integrity of barrier material, backfill, and concrete for the 2BMA and 1BRT waste vaults. These processes are interrelated and include stresses from self-weight, hydraulic forces, and deformation of the rock or compaction of backfill; concrete degradation; effects of freezing; and corrosion of reinforcement. These processes may cause a decrease in strength and induce formation of cracks and fractures affecting hydraulic properties and indirectly influencing dissolution reactions. Additionally, corrosion in rock bolts may induce rockfall from the vault walls and roof. It is recommended that SKB provide references in which the stress evaluations were performed, including descriptions of how evaluation results were used in the safety analysis.

7. SKB TR-14-01, Chapter 7, Selection of scenarios – Seismic damage

   Demonstrate that seismic damage of the 2 to 5BLA waste vaults is insignificant such that it can be dismissed in safety assessments. Section 7.6.5 of the Main Report (SKB TR-14-01) states that seismic effects on the backfilled 2BMA structure are small and the earthquake scenario relates only to the silo. The details supporting this statement are provided in the SKB safety analysis report for SFR 1 (SKB R-08-130). This statement implies that the earthquake scenario is not applicable to any other waste vaults, including unbackfilled 2 to 5BLA waste vaults. However, the ISO containers in 2 to 5BLA waste vaults are stacked (six containers assuming half-height containers) up to a height of 9.0 m (SKB TR-14-01, Figure 4-22). Seismic ground motion may induce sliding and overturning of free-standing containers. Potential kinematic instabilities may result in collisions, impacts, and drops, leading to loss of integrity of the containers and waste packages. It is recommended that SKB provide a rationale for not evaluating an earthquake scenario in the safety assessment related to long-term performance of 2 to 5BLA waste vaults.

APPENDIX 3

Suggested review topics for SSM

Important review topics for the Main Review Phase are suggested as follows, along with a description of why these are judged to be important in the context of the safety assessments.

1. Review of the significance of mechanical and chemical processes

   It is not transparent from the Swedish Nuclear Fuel and Waste Management Company (SKB) documentation (i) how the abstractions of mechanical and chemical processes affecting concrete, including uncertainties, were accounted for in the water flow and radionuclide transport modelling supporting the safety assessment, and (ii) what is the importance of these processes to radionuclide release and radiological dose consequences for the analysed scenarios. It is recommended that the reviews of mechanical and chemical processes affecting concrete be coordinated with the reviews of safety, risk, and performance assessment for thorough and efficient evaluation of these processes. Detailed review should focus on mechanical and chemical aspects that are risk-significant.

2. Review of the hydraulic conductivity and sorption properties

   The relationship of mechanical and chemical processes affecting concrete, and their associated model and data uncertainties, to the variability and uncertainty of parameters, such as hydraulic conductivity and sorption properties, should be evaluated in detail. SKB discussed uncertainties in the SR-PSU report and other supporting documents. It appears the uncertainties of mechanical and chemical processes were characterized deterministically in the SKB safety analysis, while for radionuclide transport model and dose calculations, uncertainties may have been numerically propagated with the use of probabilistic models. It is recommended that the detailed review examine (i) the SKB technical basis for selection of conservative values and bounding cases in deterministic evaluations of mechanical and chemical processes, and (ii) the sensitivity of parameters in the safety assessment results.

3. Review of complementary information

   Information provided in response to the needs for complementary information (NCI) identified in Appendix 2 of this report should be evaluated during the in-depth review phase. Some topics in the Appendix 2 NCIs may be relevant to several areas of the review of the SKB license application—not only to evaluations of concrete materials performance. Appendix 2 of this report provides justifications for the relevance of the recommended NCIs for the review of the long-term safety assessment.

4. Review of the effects of degradation on post-closure safety

   Post-closure degraded state conditions of the SFR 3 repository system should be evaluated, including quantification of hydraulic properties and uncertainties, models, and data for use in the safety assessment based on the described 10-step methodology. Features, events, and processes; relevant models, data, safety functions, and handling of uncertainties; and long-term safety assessments were discussed in Section 2.1 of this report. Quantification of the post-closure degraded conditions of the repository, data availability and adequate modelling, and consideration of uncertainties have direct implications for the post-closure safety assessment.

5. Review of the initial state conditions

   The initial state of SFR 3 building structures, waste containers, barriers, cement grouting, borehole sealing, and excavated rock vaults and tunnels should be examined. Components of the excavated vaults and designed reinforced and non-reinforced concrete structures and other engineered systems will undergo degradation—such as corrosion of steel, fracturing of steel and concrete waste packages, and fracturing of structural concrete members—during the operation period of the SFR repository. The conditions of the components at repository closure will be the initial conditions for the post-closure performance of the repository. Therefore, the conditions at repository closure may have significant implications for the long-term safety assessment.

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Preparatory review of the rock engineering and engineering geology issues related to the safety of the extension of SFR

Activity number: 3030014-1009
Registration number: SSM2015-1310
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Abstract

The Swedish Radiation Safety Authority (SSM) has received an application for the extension of SKB's final repository for low and intermediate level waste at Forsmark (SFR). The Consultants' Initial Review on SKB's applications documents with regards to rock engineering and engineering geology is summarized.

The investigations provided to support the licence application are made by SKB are of international class and technical reports were written and organized in a professional way. Given the many uncertainties associated with the design and construction of an underground repository, the width of the database, the performance of the safety assessment and the quality of reporting are judged to be of high standard. The strongest merit of SKB's application documents is that SKB already has proven records of operating SFR 1 with continuous monitoring. This experience has helped the thorough investigation necessary for the extension of the existing repository. Furthermore, extensive site investigations conducted at Forsmark for the planned deep repository of spent nuclear fuel has allowed for improvement in the general understanding of the area.

On the other hand, it needs to be mentioned that SFR is only in the initial period of its technical life time, and a lot of uncertainties still remain to be resolved, which require substantial amount of work to be conducted. This should be done through comprehensive design, engagement during construction, elaborate monitoring strategy and continued R&D programme.

There are a number of limitations and weakness noticed through the Initial Review Phase as follows;

- Determination of rock mass properties for SFR extension,
- Long-term and large-scale stability analyses,
- Effect of groundwater on stability of rock vaults,
- Effect of shoreline evolution and climatic changes on rock vault stability,
- Improved analysis on the effect of earthquakes,
- General evaluation of the location and layout of SFR 3.

Overall, SKB is recommended to perform more in-depth technical analyses and adopt newer technologies for solving the rock mechanics and rock engineering problems at SFR. Although the regulations regarding low and intermediate level nuclear waste may be less strict than for spent nuclear fuel, additional investigations are still necessary to comply with the regulatory requirements set by SSM according to the license application schedule.

The general structure, transparency and traceability of SKB's application documents are acceptable. Essential information is collected, integrated and well-presented into the Main Report with relevant citation to the Main References. Most of the documents are accessible to the general public and their presentations are judged to be transparent. Nonetheless, it needs to be pointed out that more thorough and traceable verification of the used numerical codes and models for this application is necessary. Some of the mechanical parameters such as in-situ stress presented in the reports are not compatible with each other and this shows that the process of safety assessment has room for improvement.

Based on the findings from the Initial Review Phase, topics which require additional review for the Main Review phase are as follows in the order or priority:

- Long-term stability of SFR chambers and the impact of climate changes and future glaciations,
- Effect of earthquakes on nearby faults and the stability of SFR caverns,
- Systematic methodology for rock mass property determination,
- The effect of rock support degradation on the long-term performance of SFR,
- Suitability of the location and layout of the SFR extension.

Sammanfattning

Strålsäkerhetsmyndigheten (SSM) har erhållit en ansökan från Svensk kärnbränslehantering AB (SKB) om att utöka lagringskapaciteten för kortlivat låg- och medelaktivt kärnavfall vid den nuvarande anläggningen SFR i Forsmark. Denna rapport behandlar de externa konsulternas inledande granskning av ansökan med avseende på de bergtekniska och ingenjörsgeologiska aspekterna.

De undersökningar som genomförts av SKB och dess konsulter för att underbygga innehållet i ansökan är av hög internationell klass och de tekniska undelagsrapporterna till ansökan är professionellt och väl organiserade och skrivna. Utgående från de många osäkerheter som hänger samman med utformning och konstruktion av en undermarksanläggning i berg är omfattningen på data i platsundersökningen, utförandet av säkerhetsanalysen samt kvalitén på redovisningen av undersökningsresultaten av hög standard. Den allra största förtjänsten vad gäller innehållet och nivån på de ingående dokumenten i ansökan är SKB:s tillgång på omfattande mätresultat och kunskaper från driften av nuvarande SFR1. Erfarenheten från driften av SFR 1 har varit vägledande för undersökningarna och platsvalet för ökad lagringskapacitet i den planerade anläggningen SFR 3.I tillägg till de utförda undersökningarna i SFR-området har SKB dragit nytta av metoderna och resultaten från platsundersökningar som man utfört väster om SFR-området för det planerade slutförvaret för utbränt kärnbränsle.

Det bör också påpekas att livstiden för SFR 1 befinner sig idag i en början och att det finns flera osäkerheter beträffande det långsiktiga beståndet av anläggningen vilket kräver ytterligare arbete för att lösa. Detta kan ske genom ett övergripande designarbete, engagemang under konstruktionsarbetet, väl utformade fältmätningar och kontinuerligt genomförda forskings- och utvecklingsprogram..
.

Det finns ett antal begränsningar och svagheter i ansökan som har framkommit i den inledande granskningsfasen

- Bestämning av bergmassans egenskaper för SFR3
- Långtids och storskalig stabilitet
- Grundvattnets inverkan på stabiliteten för bergsalarna
- Effekten av strandlinjens utveckling och klimatförändringar för bergrummens stabilitet
- Förbättrade analyser av effekterna av jordskalv
- Generell utvärdering av lokslisering och layout av SFR 3

En övergripande synpunkt är att SKB rekommenderas genomföra mer djupgående tekniska analyser och tillämpa mer moderna metoder för analys och modellering av bergtekniska och ingenjörsgeologiska problem för byggandet av SFR 3. Även om regler och anvisningar för deponering av låg- och medelaktivt avfall är mindre krävande och omfattande jämfört med motsvarande för högaktivt avfall krävs mer omfattande undersökningar för SFR för att leva upp till innehållet i SSM:s bestämmelser och anvisningar

Den övergripande strukturen, transparencen och spårbarheten hos SKB:s lämnade dokument till ansökan är tillfredsställande. Den viktigaste informationen har samlats in, integrerats och bearbetats på ett i stort tillfredsställande sätt i Huvudrapporten och med relevanta hänvisningar till bakgrundsrapporterna. De allra flesta bakgrundsrapporter är allmänt tillgängliga och innehållet rapporterna är transparent. Det bör dock tilläggas att mer omfattande och spårbar information om tillämpade

matematiska modeller och numeriska beräkningsprogram efterlyses. Flera av de bergmekaniska parametrarna, så som exempelvis bergspänningarna som redovisas i olika rapporter, är inte kompatibla med varandra och detta visar att säkerhetsbedömningen har plats för förbättringar.

Baserat på resultaten från den inledande granskningsfasen lämnas följand förslag i prioritetsordning till frågeställningar som kräver fortsatt och fördjupad granskning under den följande, fördjupade granskningsfasen:

- Långsiktig stabilitet av bergsalarna i SFR och inverkan av klimat-förändringar och kommande glaciationer
- Effekten av jordskal på närbelägna förkastningar till SFRoch inverkan på stabiliteten hos bergsalarna i SFR
- Metodik för systematisk bestämning av bergmassans egenskaper ,
- Effekterna av degradering av bergförstärkningarna i SFR,
- Lämpligheten av föreslagen lokalisering och design av SFR 3

Contents

1. Introduction

1.1. Background

The Swedish system for management of short-lived, low- and intermediate level-waste from nuclear power plants and other nuclear activities such as industry, research and medical care, includes facilities for treatment, transportation, interim storage and final disposal. Most of these waste facilities are operated by the Swedish Nuclear Fuel and Waste Management Co., SKB. A repository for short-lived, low- and intermediate radioactive operational waste (SFR) at Forsmark in the municipality of Östhammar has been operated by SKB since 1988 (SKB TR-14-01). The repository is located below the Baltic Sea and covered by about 60 meters of granitic rock. The underground part of the existing facility, SFR 1, consists of four waste vaults, plus a 70-metre-high vault with a concrete silo (Figure 1). Today, operational waste from the nuclear power plants and from other nuclear facilities is disposed of in SFR 1.In the future, the nuclear power plants in Sweden will be decommissioned and dismantled and waste is planned to be disposed in SFR. A need for additional disposal capacity in SFR has been accentuated by the closure of the two reactors in Barsebäck. Additional disposal capacity is needed also for operational waste from nuclear power units in operation because their operating life-times have been extended compared with what was originally planned. SKB therefore plans to extend the facility with a new repository SFR3 directly adjoining the existing SFR 1. In addition, the extended part of SFR will be used for interim storage of long-lived low- and intermediate-level waste awaiting final disposal in a future repository for long-lived waste (SFL), which is planned to be in operation around 2045.

The extension, SFR 3, will be built with a rock cover of about 120 m, which is about the same level as the bottom of the existing Silo. The underground part of SFR 3 will consist of six new waste vaults. Additional operational waste and the waste from decommissioning of the Swedish nuclear power plants and other nuclear facilities will be disposed of in SFR 3. There will also be room for disposal of nine reactor pressure vessels from boiling water reactors. After the extension is completed, SFR will have three times its current storage volume (SKB TR-14-01).

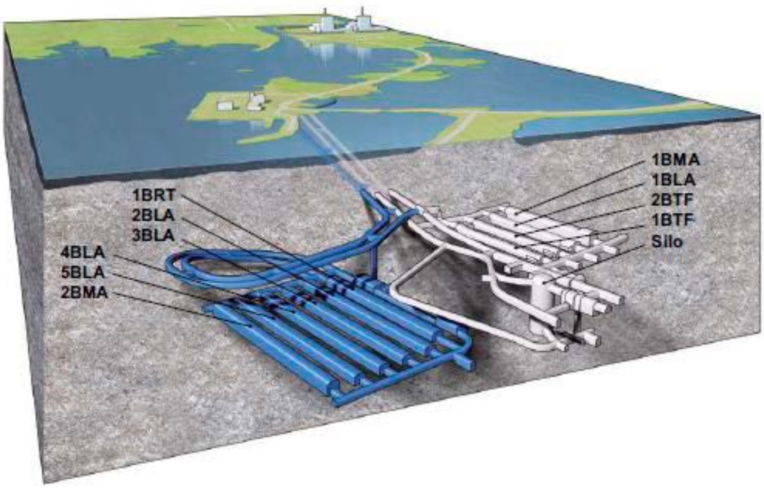


Figure 1: The existing SFR1 (grey), the extension SFR3 (blue) and access tunnels (SKB TR-14-01).

The Swedish Radiation Safety Authority (SSM) has received an application for the extension of SKB's final repository for short-lived low- and intermediate level waste at Forsmark (SFR-U) on the 19 December 2014. SSM is tasked with the review of the application and will issue a statement to the Swedish government that will decide upon granting the license. An important part of the application is SKB's assessment of the long-term safety of the repository, which is documented in their safety analysis named SR-PSU.

SSM's review procedure is divided into an Initial Review Phase and a Main Review Phase. The assignment results presented in this report concern the Initial Review Phase. In this phase there are several objectives. Firstly, a broad understanding of the content of the application should be achieved. Secondly, it shall be assessed if SKB's documentation is understandable and complete with regard to the information that is needed for assessing the application. SSM will ask SKB for complementary information on these issues at the end of the Initial Review Phase. Thirdly, the key review topics from the Main Review Phase shall be identified. These are topics that will have a significant impact on SSM's assessment.

Detailed analysis of specific issues will be handled in the Main Review Phase and it is not part of this assignment. In the Main Review Phase, SSM will also determine if SKB fulfils all necessary regulatory criteria.

1.2. Assigned topics and reviewed reports

SKB's application documents are composed of the main report, twelve main references and a large number of additional references (Figure 2).

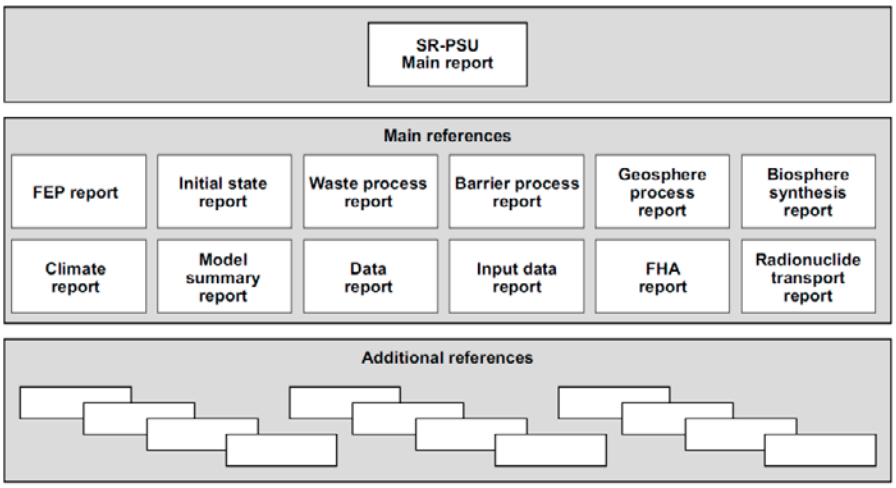


Figure 2: The report hierarchy of the safety assessment, including the main report, main references and additional references in the SR-PSU long-term safety assessment (SKB TR-14-01). Reports covered in the current Initial Review Phase are main report, five reports from main references and five reports from additional references. See Appendix 1 for the full list with relevant chapters covered in this initial review report.

This assignment covers the rock engineering and engineering geology issues related to the operational and long-term safety of the extension of the SFR repository.

SSM has defined the scope of service for the review into: a) general instructions and b) specific description of the assignment. According to the general instructions, the most important review topics should be presented, the relevant models, data and safety functions should be assessed including uncertainties and suggestion of any complementary information and the overall quality of SKB's documentation. According to the specific description of the assignment, the deepening of the review shall focus on the aspects of:

- Functional suitability of the facility with respect to operations for storage and deposition of the waste,
- Integration with the existent parts of the facility,
- Vicinity between the access tunnels and the seashore,
- Rock mass properties and stresses obtained from the site investigations, and
- Evolution of the conditions during relevant times in SKB's safety analysis.

Rock engineering and engineering geology issues concern the stability of the rock chambers and pillars during operation and possible degradation processes before and after closure of the repository. The effects of climatic changes and glaciation on the stability of the excavations should be also considered. Even the large scale stability of the repository as a whole with respect to the sea bottom should be looked upon together with the risk related to the occurrence of earthquakes during operation and after closure. A list of topics for which a deeper review of the application should be carried out in next review phase is listed as Appendix 3. For each topic, the importance for the safety of the repository will be highlighted, and priority will be given to each topic based on its importance for the continuation of the review.

The list of SKB reports and documents that have been reviewed in this assignment is as follows with its abbreviation if applicable. The chapters covered for the Initial Review Report are listed in Appendix 1.

- Safety Analysis for SFR, Long-term safety, Main report for the safety assessment SR-PSU (Main report, SKB TR-14-01)
- Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark (SKB TR-11-04)
- Data report for the safety assessment SR-PSU (Data report, SKB TR-14-10)
- FEP report for the safety assessment SR-PSU (FEP report, SKB TR-14-07)
- Initial state report for the safety assessment SR-PSU (Initial state report, SKB TR-14-02)
- Model summary report for the safety assessment SR-PSU (Model summary report, SKB TR-14-11)
- Input data report for the safety assessment (Input data report, SKB TR-14-12)
- A seismic evaluation of SFR. Analysis of the Silo structure for earthquake load(SKB R-13-52)
- Long-term stability of rock caverns BMA and BLA of SFR, Forsmark (SKB R-13-53)

- F-PSAR- General Description, Part 1, Chapter 5, Description and function of SFR (SKB Document ID 1245480, in Swedish)
- F-PSAR SFR –General part 1, Chapter 5 – SFR Closure Plan (SKB Document ID 1358612, in Swedish).

1.3. Structure of the Initial Review Report

The current review report starts in Chapter 2 with an overall review on SKB's safety assessment for SFR-extension (SR-PSU). Detailed review comments on each of SKB report are followed in Chapter 3 in order to support the overall review comments. Chapter 4 is devoted to suggested topics that deserves more detailed and elaborate review during SSM's Main Review Phase. The final chapter concludes with general statements on SKB's application documents focusing on its traceability and technical soundness. Appendix 1 presents the concise summary of the review comments on SKB reports in tabular form, and Appendix 2 provide a list of complementary information the Consultants suggest to be requested from SKB. Finally, suggested review topics requiring substantial additional work during SSM's Main Review Phase are summarized in Appendix 3.

2. Main topics of importance for the safety of the SFR repository

Main topics of importance in the Initial Review Phase are summarized in this chapters based on the evaluation on the scientific quality and soundness of the application documents. Special focus was given to the adequacy of relevant models, data, safety functions and the handling of uncertainties.

2.1. Stability of rock chambers and pillars of SFR

2.1.1. Site investigations on rock engineering properties for the SFR extension

SKB has decided not to collect any new data for the establishment of the rock mechanics site descriptive model for the extension of SFR. The description of the rock mechanics parameters (strength, deformability and rock stress) are based on old data collected during the planning and construction of existing SFR 1 and data from the investigations for the Forsmark site for a repository of spent nuclear fuel. The rationale for this decision is not presented SKB's report.

The properties of rock mass are different from those of intact rock, and there are numerous techniques to determine or estimate them. Although SKB seems to have recognized the importance of such distinction, no due attention was given to more elaborate testing and analysis to determine the rock mass properties such as elastic modulus, Poisson's ratio and strength parameters of the rock mass based on empirical relations or on the properties of the intact rock and fractures. Table 6-8 of site description report (SKB TR-11-04) show the list of rock mass properties. However, there is no physical compelling explanation how this determination was done. Considering that SKB has developed systematic approaches to determine the rock mass properties both numerically and empirically (Röshoff et al., 2002; Olofsson and Fredriksson, 2005), not using the SKB's own methodology as was developed and applied for the site investigation of the final repository for spent nuclear fuel is disappointing. The key consideration in determining the rock mass properties is the highly non-linear fracture behaviour and this has to be properly considered for a design in a fractured rock mass as was demonstrated in Min et al. (2005).

2.1.2. Long-term and large-scale stability analyses

Long-term and large-scale stability analyses presented in SKB's application leaves much room for improvement. The only relevant additional reference report in this area only consisted of limited analysis on existing two rock vaults BMA and BLA of SFR 1 with consideration of rock fracture property degradation. No stability analysis was conducted on SFR 3 which is the main target of the licence application. Since it is the extension of SFR that is being reviewed rather than continuation of SFR 1, there must be extensive stability analysis ensuring that the current design of SFR 3 is safe and no significant rock fall or loosening of adjacent rock block are anticipated.

More comprehensive plan and analysis to ensure the stability of SFR 3 is needed. Although the silo is an existing structure, renewed stability analysis has to be provided considering its importance for the long-term safety of the completed SFR and its large scale structure. Most of stability analyses were conducted about thirty years ago when it was first built (Carlsson and Hedman, 1986; Carlsson and Christiansson, 1986; Larsson and Christiansson,1986; Stille and Fredriksson, 1988; Björk and Malmström, 2004).

Modern coupled hydro-mechanical analysis with rock displacement and inflow will highly improve the understanding on the hydraulic and mechanical behaviour of underground structures at SFR.

Another important aspect is the direction of waste vaults in SFR 3. According to the layout (Figure 1), vaults are directed toward North-East direction which is almost perpendicular to the direction of major horizontal stress, which is determined to be 142°from North. There must be compelling argument for this decision. If the decision is based on preferred choice of larger horizontal stress to generate arch effect, a more specific explanation need to be presented by SKB and to be evaluated by SSM. Even if existing underground facility in SFR 1 did not show notable instability problem, SFR 3 need more careful approach since it is located around 60 m deeper than SFR 1 which will exert higher stress.

It appears that no effort has been made to calibrate the values of the displacements predicted by the numerical model against any in-situ measurement from the construction and operation of SFR 1. The Authors of the report are not sure if there has been any in-situ monitoring of the displacements from the construction and operation of SFR 1 and this lack of information needs to be explained by SKB. As there probably are a lot of monitoring data, SKB should be in a good position to be able to use monitoring data and calibrate the numerical model. This will give the opportunity to validate the numerical results.

We believe comprehensive long-term and large-scale mechanical stability analysis of SFR extension is critically important for the safety and this has to be appropriately considered according to the license application schedule.

2.1.3. Effect of groundwater

SFR is essentially a subsea underground structure and coupled hydro-mechanical process will play an important role in the stability of chambers and tunnels.
A major concern is that stability analysis is conducted in a purely mechanical manner. The existence of water pore pressure can deteriorate the frictional properties of fractures and can reduce the effective normal stress, which make the fracture more vulnerable to sliding. More modelling or observational evidence considering the pore pressure at the SFR site is needed.

Measured inflow into the cavern is very important monitoring data and SKB is commended on this work (Figure 3). Measurements of the inflow to the SFR facility have been carried out regularly since 1988. The total inflow in 1988 was about 720 l/min, and this decreased to 285 l/min in 2010. The reduction of rate of inflow and reduced pumping costs are important factors for the operational cost of the repository. Increased effective normal stress, two-phase flow and chemical precipitation have been suggested by SKB as possible reasons for the diminishing inflow with time (SKB, 2013). Decrease of water pressure in the fractures and corresponding effective normal stress is an important hydro-mechanical mechanisms and the rock mass response has to be explained in conjunction with the measured ground water pressure around the rock caverns.

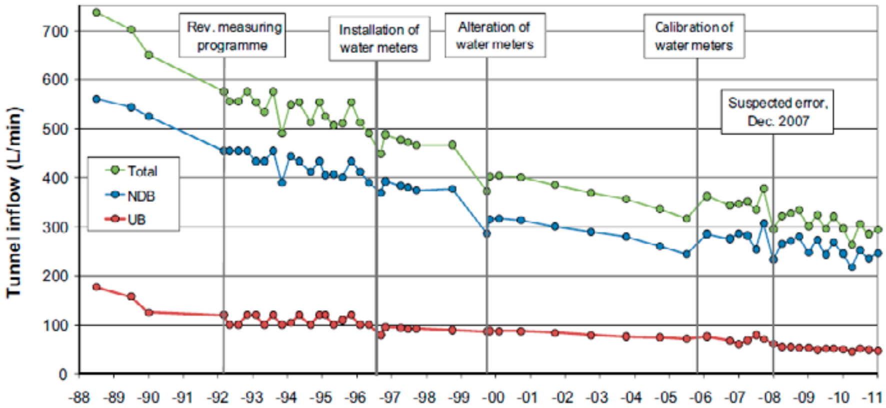


Figure 3: Inflow of groundwater to the existing SFR between 1988 and 2011. UB and NDB refer to drainage of the pumping pits in the operational area and in the lower construction tunnel, respectively (SKB TR-11-04).

2.2. Rock engineering and engineering geology issues related to climate changes and earthquakes

2.2.1. Shoreline evolution and climatic changes

SFR is designed as a subsea hard-rock facility which is reached via access tunnels from a surface facility. SFR 1, which comprises of a silo and four waste vaults located about 60 m beneath the surface of the sea with the bottom of the silo located about 70 m beneath. SFR 3 is planned to have six waste repository vaults that will be located at about 130 m beneath the surface of the sea (Main report, SKB TR-14-01).

Changes in the shoreline position in the Forsmark area are determined by the opposing contribution of eustasy (i.e., changes in sea level) and isostasy (i.e., vertical displacement of earth crust due to rebound). Glacial Isostatic Rebound (GIA) is expected to be around 6 mm/year within the assessment period. It is expected to take 1,200 to 2,200 years for the seabed on top of the rock cavern to be exposed at surface. The effect of this uplift has never been investigated by SKB in the context of coupled hydro-mechanical processes occurring near the underground chambers. The long-term change will have impact on groundwater pressure distribution and in-situ stress conditions. These changes might then have impact on the mechanical stability and can trigger earthquakes along critical loaded faults. This change will also affect the saturation time of engineered barriers structures such as bentonite backfill and plugs. Other unforeseen changes can occur and their impact on safety assessment is of great importance in view of the retention of released radionuclides.

2.2.2. Earthquakes

Earthquake can affect the stability of rock and the stability of the whole repository. Although seismic activity in Fennoscandian Shield is currently low, large earthquakes over very long time scales cannot be ruled out. Therefore, the earthquake scenario is now included as less probable scenario in SKB license application, which is reasonable.

It is noted that SKB's earthquake analysis (Georgiev, 2013) was conducted on continuum concrete Silo structure and no consideration was made regarding the effect of rock fractures and the interaction between rock mass, engineer barrier and concrete structure. Important conclusions from the content of the earthquake report is that the SFR Silo structure will maintain its integrity under the loading from an earthquake with an annual exceeding frequency of 10^{-5}. However, with probability level of 10^{-6} and 10^{-7}, the structural integrity cannot be guaranteed. Extensive cracking in the outer wall, tension in the casting joint between the slab and outer wall and inner walls resulted from calculated stresses significantly above the tensile limit strength of concrete.

It is emphasize that more detailed, systematic earthquake analysis is necessary for underground rock chambers both in SFR 1 and SFR 3. The distinctive insight that can be gained from earthquake analysis in underground rock structure is the role of numerous fractures and faults existing in the selected rock mass. Rock fractures and faults can slide due to earthquakes and this will have impact on stability. Also sliding fractures can induce dilation resulting in larger transmissivity to fluid along the fractures. Therefore, it is important to conduct earthquake analysis in a fractured rock mass so that the interaction between rock mass, engineer barriers and concrete structure can be considered.

It is noted that SKB's SFR is a unique facility of its kind in the world, and it is urged that more pioneering efforts be made by adopting state-of-the-art analyses and technology. In particular it is recommended accurately measuring fracture displacement in both shear and normal direction, and thereby establishing long-term monitoring strategy to validate results from modeling is recommended (Guglielmi et al., 2015).

2.3. Layout and location of the SFR extension

The data upon which the site descriptive model for SFR is based were collected mainly from investigations carried out during the planning and construction of SFR 1 (1980-1986), the site investigations for the final repository of spent nuclear fuel (2002-2007) and the site investigations for the extension to construct SFR 3 (2008-2010). Already at an early stage of the investigations, the area southeast of the existing SFR 1 was selected and the investigations were concentrated to this area despite the fact that there were indications of better rock masses and less faults east of SFR 1. These areas have never been considered for the extension of SFR but have a potential to be much better suited. This statement is based on information derived from the presented airborne geophysics in the regional investigation area (SKB TR-11-04).

The selected site for SFR 3 is located in a highly anisotropic, inhomogeneous, and complex rock mass with a large variety of different rock types, strong plastic and brittle deformation and high frequency of major faults. In addition, the selected site is squeezed in between a set of prominent, mayor fracture zones forming a southern and northern boundary belt where the southern boundary belt contain the Singö fault which is the most prominent fault in the eastern part of the county of Uppland. In summary, the bedrock geology, structure geology, hydrogeology and rock mechanics is highly variable and complex and therefore not recommended for construction of an underground rock facility. However, the construction and present stability of SFR 1 with similar geology and rock properties as for SFR 3 show that an extension and location to the suggested site with similar conditions as for SFR 1 is possible, although not recommended. An even deeper location automatically leads to higher rock stresses, but the ratio between rock strength and rock stress would remain relatively high and most probably be on the safe side.

At present the true depth extension and characteristics of the sheet joints in the upper 150 m of the bedrock is of concern with respect to the suggested depth of the suggested underground facilities of SFR 3.

Furthermore, the possible impact of a final repository for nuclear spent fuel needs to be evaluated. Disposal of spent nuclear fuel generates heat and thermal stresses and this can induce micro-earthquakes or trigger geological earthquakes. Systematic seismic investigation needs to be made on this regards.

3. Detailed review remarks on SKB's application documents

3.1. Safety Analysis for SFR long-term safety (SKB TR-14-01)

3.1.1. Introduction

This document is the main report of the SR-PSU and is the main component in SKB's licence application to extend SFR. The long-term post closure safety of the extended repository has to comply with the Swedish Radiation Safety Authority's regulations concerning safety and protection of human health and the environment in the long-term perspective. The time frame for the assessment of the risks and environmental impact is set by SKB to be maximum 100,000 years. The central conclusion of this safety assessment SR-PSU is that the extended SFR repository (SFR 1 and SFR 3) meets regulatory criteria with respect to long-term safety considering the sufficiently limited activity of short-lived radionuclides and sufficient retention of radionuclides escaping the repository.

SKB has defined two safety principles for the post-closure safety for the SFR repository: i) limitation of the activity of long-lived radionuclides and ii) retention of radionuclides by performance of engineer barriers and the repository design such as waste containers, engineer barriers in the vaults, low water flow and suitable geochemistry of the rock mass. The Main report also contains descriptions on how the requirements in the regulations set by SSM are handled in the long-term safety assessment by referring to relevant sections or through a description directly in the appendices. The principal acceptance criterion expressed in SSMFS 2008:37 concerns the protection of human health and requires that "the annual risk of harmful effect (cancer and hereditary effects) after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk" (SSMFS 2008:37). The risk limit corresponds to an annual effective dose limit of about $1.4 \cdot 10^{-5}$ Sv, which corresponds to around one percent of the effective dose due to natural background radiation in Sweden. Besides risk limit, SSMFS 2008:37 also requires that protection of the environment is considered. Furthermore, SSMFS 2008:21 requires descriptions of the evolution of the biosphere, geosphere and repository for selected scenarios; and evaluation of the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties (SSMFS 2008:21).

Figure 4 shows the overview of the ten steps used for the safety assessment. Initial state after closure, external conditions such as climate-related processes, and internal processes within the repository system such as thermal, hydraulic, mechanical and chemical processes acting in the repository system are included.

The current review focus on the rock engineering and engineering geology aspect in dealing with safety assessment. Special focus is given to shoreline evolution, mechanical processes in the repository, earthquake scenario, and requirements and constrains to the conclusions in relation to construction and operation of repository.

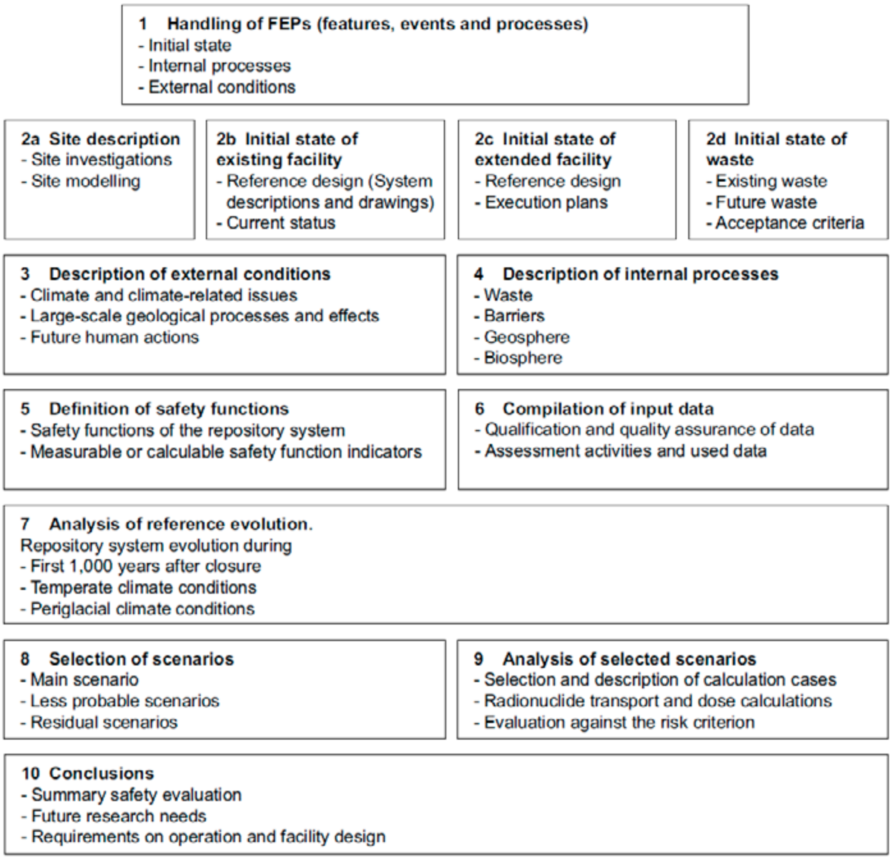


Figure 4: Overview of the ten steps used for the long-term safety assessment SR PSU (Main Report, SKB, 2014).

3.1.2. Construction and operation of rock vaults and Silo

In the Main Report, it was acknowledged that the requirements on construction, for example the use of rock support, the choice between different materials, and situations where special precautions need to be taken or special procedures have to be used during blasting, need to be specified. Even if it may not be necessary to provide all the details of underground construction, the basic requirements and specification, for example contained in the EUROCODE, has to be clearly set. More specific information is required in this regards including monitoring strategy on mechanical deformations, water inflow and fault displacement. If possible, the criteria for managing the outcome of the monitoring have to be given.

Mechanical stability analysis of the planned six vaults need to be included in the reference documents. These underground structures will be built beside the existing SFR 1 and the impact of this has to be fully investigated in construction phase and long-term safety considering the hydraulic and mechanical impacts during construction and operational stages. Numerous possibilities such as excessive inflow, ground vibration due to blasting or stress concentration due to nearby opening have to be explicitly considered. Mechanical evolution is an important external condition that has to be considered and the uncertainty still remains because stability of silo and new vaults were not analysed.

Also the impact of the repository of nuclear spent fuel on SFR should be also included. Results from recent modelling of far-field and near-field thermomechanical modelling by Min et al (2013, 2015) has shown that the thermal loading from the repository of spent nuclear fuel together with the existing stress field at the site can generate substantial thermal stress, which then causes shear displacement along pre-existing fractures in the surrounding of the repository. The fracture shearing can cause transmissivity changes and can trigger the onset of earthquakes in the area of SFR. Although the ranges of notable thermal stress seems to be limited to in the order of a few hundred meters but a more systematic consideration will be necessary and in particular the possibility that existing faults in the spent fuel repository reaches to or are interlinked with faults in the SFR area. It would be also more reasonable and appealing to the general public to fully explain the possible interactions between SFR 1, SFR3 and future geological repository of spent nuclear fuel.

3.1.3. Impact of shoreline evolution

Changes in the shoreline position in the Forsmark area are determined by the opposing contribution of eustasy (i.e., changes in sea level), and isostasy (i.e., vertical displacement of earth crust due to rebound). Annual uplift is expected to be 6 mm/year, which means that the seabed on top of the rock cavern to be exposed to surface after around 1,000 years. More explicit modelling of these processes has never been conducted by SKB to investigate the effect of changes in hydraulic gradient, fracture pressure, in situ stress and effective stress. These changes will also affect the saturation time of engineered structures such as bentonite and sand/bentonite mixtures. Other unforeseen changes can occur and its impact on safety assessment is of great importance in view of the retention of radionuclides.

3.1.4. Safety functions

Safety functions are defined to clarify the importance of repository components for the long-term functionality of the repository and help in the formulation of scenarios. Numerous components are listed in Table 5-2 in main report with description of aspects and their importance. The mechanical stability of shotcrete and rock bolts are mentioned in the table, but its fuller explanation cannot be found. It would be reasonable to assume that the function of shotcrete and rock bolts will deteriorate with time and their impact on the safety assessment can be deemed important. Importantly this can have impact even before the closure time which is planned in 2075. The method of investigation, evaluation and the quantitative extent to which this aspect is considered should be provided by SKB. Although one can argue that the rock supports are not accounted for the future evolution of the repository, a more elaborate analysis on the physical processes affecting them and the barriers would help in gaining public confidence.

It assumed that the mechanical condition in the bedrock (page 212) and hydraulic conductivity (page 224) do not vary during the assessment period for the main scenario. Comments on bedrock including rock mechanical conditions and hydrogeology are given in Section 3.2.Comments on the safety functions of the shotcrete and rock support are given in Section 3.5 of this report. It is emphasized that an improved understanding on the fracture transmissivity change, and rock support material evolution would greatly enhance the credibility and public acceptance of safety assessment.

3.1.5. Earthquake scenario

Earthquake can affect the local stability of the rock and the stability of the whole repository. Although seismic activity in Fennoscandian Shield is currently low, large earthquakes over very long time scales cannot be ruled out. Therefore, the earthquake scenario is now included by SKB as a less probable scenario, which is reasonable.
An analysis of the mechanical consequences of an earthquake for the integrity of the silo has been conducted with three different load spectra with annual probabilities of 10^{-5}, 10^{-6} and 10^{-7} (SKB R-13-52). The conclusion from the analysis is that damage to the silo concrete structure cannot be ruled out for a load spectrum with a probability of 10^{-6}/year. The increased water flow through the silo arising from concrete barrier damage was analysed in the safety analysis. With bentonite as a flow barrier, the increased flow of water is relatively small, in the order of 1 m^3/year (Main Report, SKB TR-14-01).

It is pointed out in the review that underground rock mass and its structures were not considered in the earthquake analysis, especially with respect to the increased fracture shear displacement, which can damage not only concrete but also bentonite barrier. Therefore, assumption of intact bentonite after earthquake may not be valid. Although no delay of radionuclides in the geosphere is assumed in this scenario, the effect of an earthquake generated rock mass deformation acting on the concrete silo and bentonite should be investigated. More detailed review comments on earthquake analysis is also given in Section 3.8.

3.1.6. Summary

- The Main report provide comprehensive analysis and reference reports to support that SFR 1 and SFR 3 meet the regulatory criteria set by SSM. Analyses were carried out systematically without omission of important features, event or processes.

- There is lack of supporting reference analysis to ensure that the silo and the new vaults in SFR 3 will maintain mechanical stability over 100,000 years. The impact of existing SFR 1 on new SFR 3, or the possibility of influence from repository of nuclear spent fuel that will be built around 1.5 km away has not been systematically investigated.

- Impact of shoreline evolution due to an uplift rate of 6 mm/year can have impact on hydraulic gradient, fracture flow pressure, in situ stress and saturation time of buffer materials. Although the process has been emphasized, more explicit modelling of its impact has not been carried out by SKB.

- Safety function on shotcrete and rock bolt degradation has been mentioned in the Main report but not fully investigated.

- Earthquake scenario was considered only based on the analysis of the concrete silo without reference to the impact from deformations of the surrounding fractured rock masses. Fracture shear slip can have impact on both concrete silo and bentonite/sand mixture. The Authors believe that this impact should be calculated.

3.2. Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark (SKB TR-11-04)

3.2.1. Introduction

SKB has undertaken an ambitious and comprehensive site characterization of the area adjacent to the existing SFR site for the planned extension of the final repository for low and intermediate radioactive waste. The presented site descriptive model (SDM) completes the site investigations and reporting for the extension of SFR, SDM-PSU. The contents of the report aim at presenting the basis for the site-adapted design of the extension of the existing facility and assessing the long-term safety of the extended SFR (SR-PSU). The report has been compiled by a dozen of experts in different fields of earth sciences and engineering. Also, the contents of the report have been reviewed by SKB's own expert group SARG.

SKB initiated an investigation programme for the extension of SFR in 2008 and thereafter the site investigations started and were carried out till 2010. The Site Descriptive Model (SDM) for the SFR extension project SDM-PSU is an integrated study of geology, rock mechanics, hydrogeology and hydro-geo-chemistry.

In 2008 SKB presented the results of the SDM-Site Forsmark that contains the integrated model for the site selection of the repository for spent nuclear fuel (SKB, 2008). The methodology and to a large extent the results from the site investigations have been used in developing the SDM-PSU. SKB has performed geological mapping in the existing facilities of SFR and has collected all borehole data, including fracture logging, according to the established methodology developed in SDM of Forsmark for the spent fuel repository. At an early stage of the SDM-PSU project, SKB made the decision that a geological DFN model for all fractures of the SFR site and the extension was not needed. However, it is most likely that a DFN model of the extended area for SFR can assist in resolving some of the problems related to the complex tectonics and structural geology of the SFR area.

The regional and local SDM-PSU models presented in the report are based on data from three different stages of investigations:

- Investigations conducted prior to and during construction of the existing SFR facility, 1980 -1986.
- Site investigation for the planned final repository for spent nuclear fuel, 2002 - 2007.
- Site investigations for the planned extension of the existing SFR, 2008 - 2010.

Some of the drill cores and tunnel mapping from the planning and construction period of the existing SFR have been considered to be key data and have been used in the modelling work for SDM-PSU.

3.2.2. Model domains, model versions and preliminary layout of the SFR extension

A bedrock map over the main land and archipelago at Forsmark is presented in Figure 2-2 of the report SKB TR-11-04. SKB has omitted to present the location of the NE border of the planned final repository of spent nuclear fuel. The distance from this border to the rock chambers of the extension of SFR is about 1.5 km (Figure 5). The data used to establish the SDM-PSU are based on surface-based investigations from geological mapping of outcrops, geophysical (magnetic and seismic) data from different investigations.

In Section 2.7 of the SDM-PSU Forsmark report, SKB presents two different model volumes for the site descriptive modelling:1) a local model volume (1685 × 1550 m in plane) that hosts the existing SFR facility and the planned extension; and 2) a regional model volume that covers a larger volume and encompass the local model. The local model volume extends from elevation of +100 to -300 m while the regional model volume extends from elevation of +100 m to -1,100 m. For groundwater flow and solute transport modelling a separate even larger hydrogeological model was defined with a model volume extending vertically from +100 m to -1,100 m. The NE border of the hydrogeological model reaches the Gräsö Island east of SFR. It is not clear from the presentation of the models at what time and for which model version the location and dimension of the three model volumes were decided. Further, SKB presents no alternative model volumes or discuss pros and cons for different alternatives model volumes.

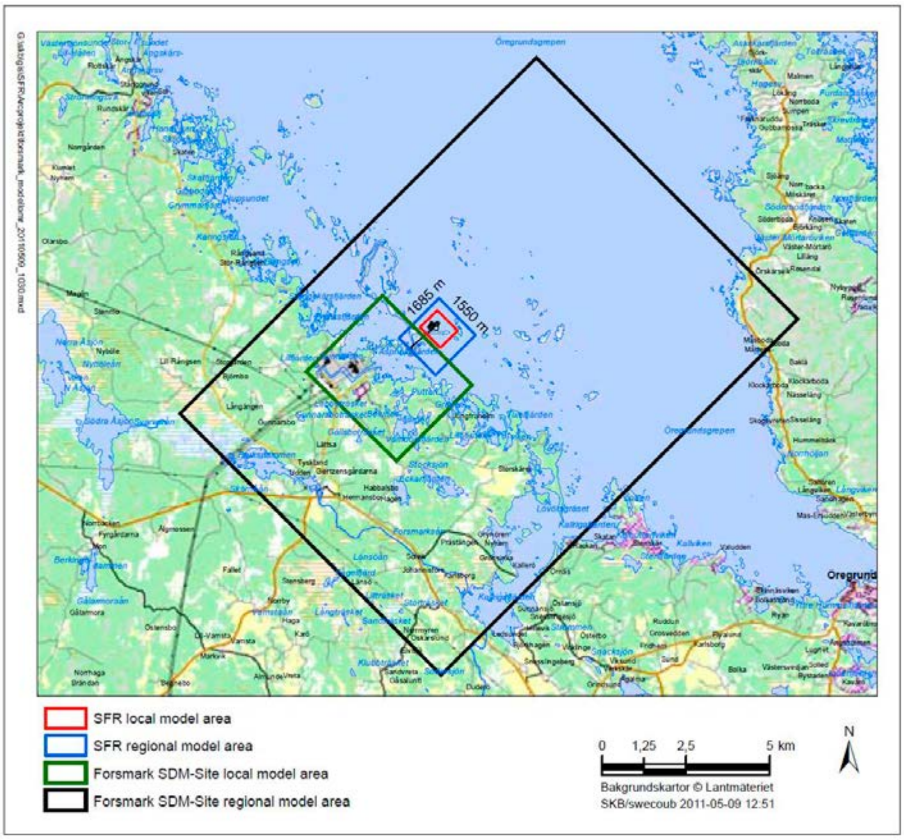


Figure 5: Regional (blue) and local (red) model areas for SFR model version 1.0 relative to the local (green) and regional (black) model areas used in the Forsmark SDM-site (SKB TR-11-04).

Four different SDM versions are presented by SKB, versions 0, 0.1, 0.2 and 1.0. For each new model version additional new information was added inside or outside the presented model volumes. Version 0 was based on data from the SFR 1 construction work and from the reported site investigations from 2008 (SKB R-08-67).

Already at the time when version 0 was presented, SKB made the decision to give priority to the area SE of the current SFR facility. Hence, there has not been a proper evaluation and public release of different alternative locations for the extension of SFR. During the SR-Site project for the location of the final repository for spent nuclear fuel (Figure 4-6, SKB TR-11-01) SKB presented a map of areas affected by strong ductile deformation in the area close to Forsmark. On this map, SFR and the suggested extension is located in the area inferred to be affected by higher ductile strain. This situation results in a complex mixture of different rock types, more or less strong foliation and folding with weakening of the strength properties, which is repeatedly mentioned in the description of the bedrock geology in the SDM-PSU Forsmark report.

The location of the planned extension of SFR is attractive due to the proximity to the existing facilities and the relative short length of the access tunnel (Figure 2-10, SKB TR-11-04, Figure 6 in this report).

A location of the extension of SFR towards NE and close to the NE border of the regional model could have been an alternative. From existing information about the geophysics, bedrock geology and major deformation zones, the bedrock at that area has favourable magnetic properties (Figure 9-2), is located north of the Northern Boundary Belt (Figure 9-9) and seems to consist of a large homogeneous area of granite, metamorphic, aplitic rock (Figure 2-2). The slightly longer transport tunnel is of course a negative factor compared with the suggested location by SKB.

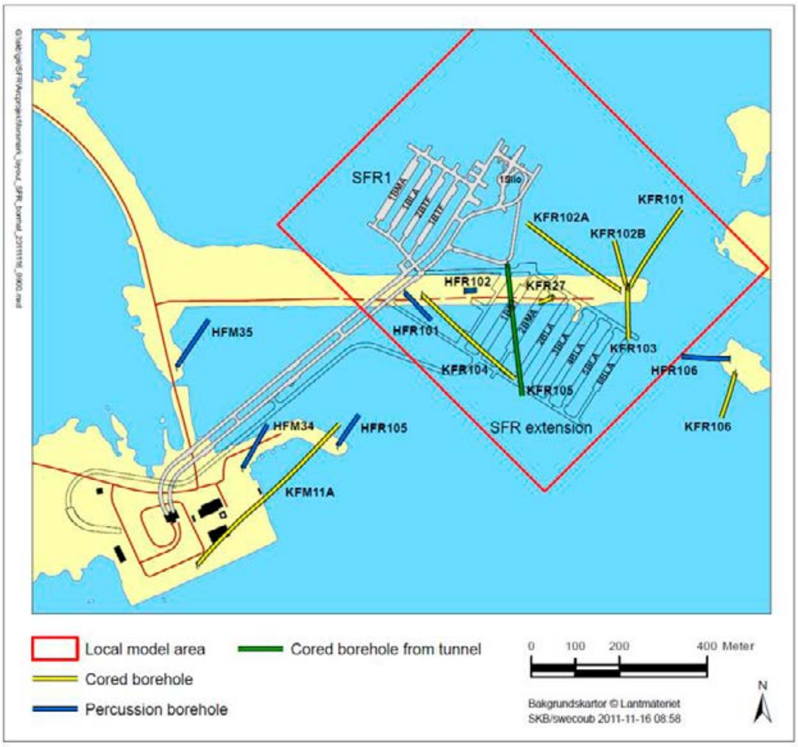


Figure 6: Preliminary layout of the SFR extension relative to the existing SFR 1 and the local model area together with the Forsmark site investigation boreholes and the boreholes from the SFR extension drilling campaign (SKB TR-11-04).

Model version 0.1 contains all modelled deformation zones according to SKB's methodology. In the models all deformation zones with a length ≥ 1,000 m are included in the regional model and length ≥ 300 m for the local model. Version 0.2 model of the geological and hydrogeological model is not presented by SKB. No bedrock DFN model was developed in the site investigations. Model version 1.0 provides the framework for the hydrogeological and hydro-geochemical modelling and other disciplines. A hydrogeological DFN model was developed in version 1.0.

At an early stage of the site investigations SKB suggested the planned extension of SFR to be in the area south-west of the existing facility and at the same depth ca -60 m level.

The SFR extension will consist of six rock chambers for low and intermediate waste and one chamber for interim storage of reactor vessels. The area where the rock chambers and tunnels are located is expected to be 200×300 m and the total excavated volume will be about 500,000 m^3. The design lifetime of the open facility is expected to be 100 years.

3.2.3. Bedrock geology

The SFR version 1.0 geological model includes both rock domain and deformation zone sub-models. The geological modelling work presented in model version 1.0 is performed in accordance with SKB's established methodology using the Rock Visualisation System (RVS) and the results are presented in a local model volume to a depth of -300 m level and a larger regional model to a depth of -1,100 m. The local model contains four rock domains (RFR01 to RFR04) and deformation zones with high and medium confidence (ZFM). Data from eight new cored boreholes plus data from the SR-Site investigations and 32 boreholes drilled during the construction of the existing SFR are included in the models together with data from tunnel mapping of exposed areas in the tunnels of the existing SFR.

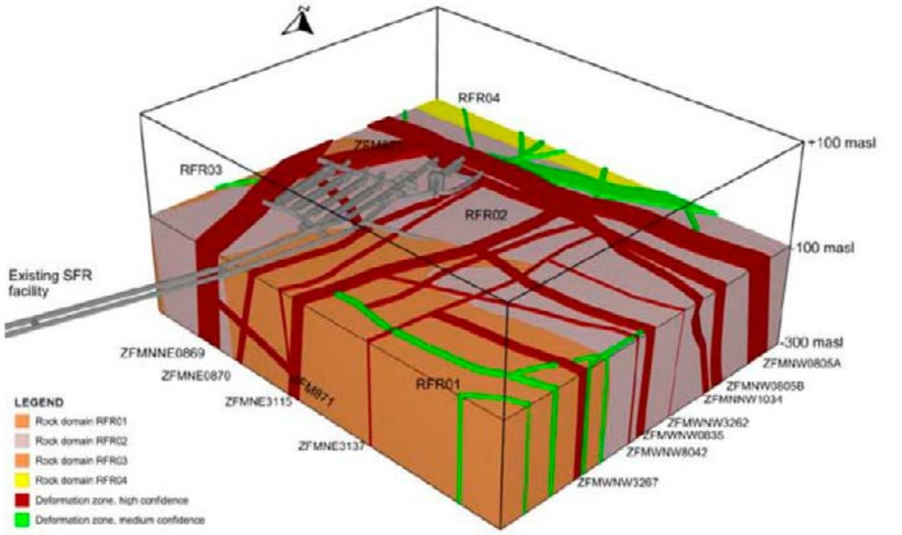


Figure 7: Rock domains and deformation zones included in the SFR local model, version 1.0. The relationship to the existing SFR underground facility is illustrated by a horizontal section at −100 m elevation, viewed against the north. Note that parts of the Silo and the lower construction tunnel (NBT) are beneath the section SKB TR-11-04).

The existing SFR facilities and the proposed extension are located in a tectonic block of fine-to medium-grained metagranodiorite (to granite) intermixed with large portions of metavolcanic rocks in rock domain RFR02. Other important rock types in rock domain RFR02 are pegmatitic granites, pegmatites, granites and amphibolites (Figure 7 and Figure 8). Rock domain RFM02 in the local model is characterised by both compositional heterogeneity by the different rock types and structural anisotropy from the foliation and mineral lineation. The existing SFR facility and the planned extension lie in a tectonic block that is bounding to two broad belts consisting of ductile and brittle deformation zones called Northern boundary belt and Southern boundary belt. Within the block there are about a dozen steeply dipping deformation zones striking NW-SE and NE-SW. In conclusion and in comparison to the tectonic lens selected for the location of the final repository for spent nuclear fuel, "the SFR area is highly variable and heterogeneous in terms of the distribution of different rock types" (cit. p.75, SKB TR-11-04).

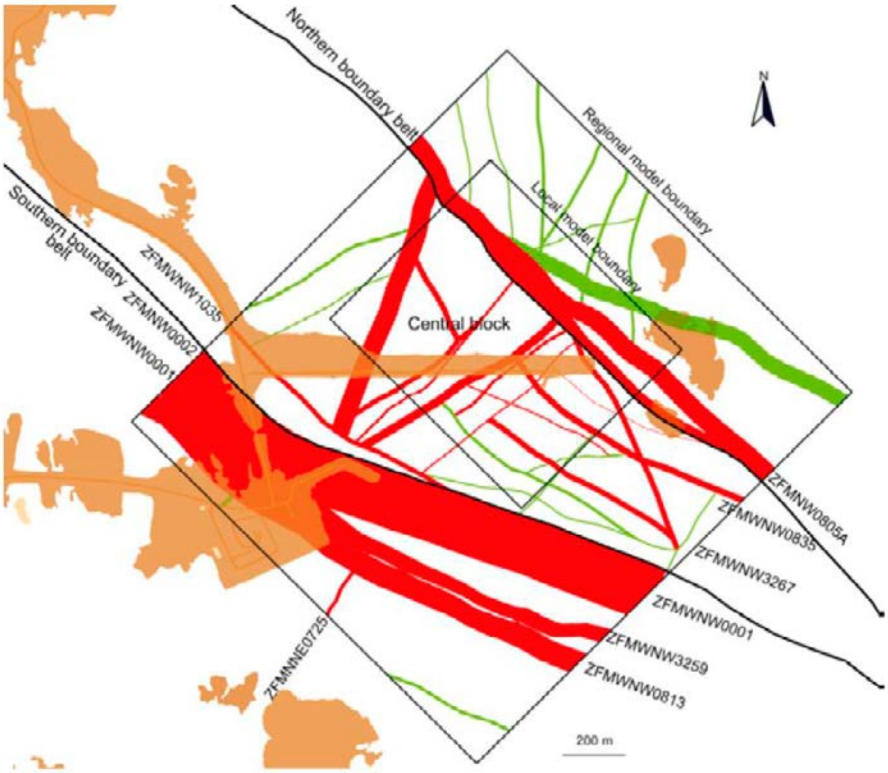


Figure 8: Intersection at the current ground surface of deformation zone traces of all sizes inside the regional model volume. The regional deformation zones ZFMWNW0001 and ZFMNW0805A, along with their major splays, form the general southern and northern boundaries of the central SFR tectonic block, respectively. Confidence in existence: high = red, medium = green (SKB TR-11-04).

An illustration of the lithological heterogeneity of the rock mass in the block between the two boundary belts is presented in Figure 5-5 of SKB TR-11-04. The ductile structures like tectonic foliation, fold axes, mineral stretching and lineation are all plunging WNW-ESE to NW-SE. The observations from the existing SFR tunnels confirms these orientations for the ductile structures and the data support the idea that ductile structures were generated by folding and stretching along the direction of the fold axis.

No fracture domain modelling, statistical analysis and DFN modelling of brittle deformation structures were performed. A simple comparison of mean fracture frequency from areas outside the deformation zones in rock domains RFR01 and RFR02 show minor differences. Of special importance for the rock mass as a whole is the dominance of the open and partly open horizontal fractures in particular above ca -200 m elevation. The sheet joints are assumed to have been generated from unloading of sedimentary rock cover and repeated deglaciations. In general a deeper location of the SFR extension will lead to less groundwater inflow to the underground openings and tunnels.

3.2.4. Rock mechanics

SKB has decided not to collect any new data for the establishment of the rock mechanics site descriptive model for the extension of SFR. The description of the rock mechanics parameters (strength, deformability and rock stress) are based on old data collected during the planning and construction of existing SFR, and data from the Forsmark site investigations for the repository of spent nuclear fuel. The rational for this decision is not presented in the report. The consequences of using just old data mean that the old rock type nomenclature has to somehow be transformed to the new rock type and rock mass nomenclature established for the spent fuel repository, data of single fracture stiffness testing produced with old equipment are used. Furthermore, most of the data obtained for the site investigations for the spent fuel repository are valid for rock volumes at elevation between -400 and -500 m. The depth of the planned SFR extension is ranging from -60 to -200 m elevation.

The strength and deformability of the different rock types from the site area of the extension have not been investigated as SKB have these data from the construction of the existing SFR 1. Also, SKB has decided that no transport and thermal properties were needed for SDM-PSU. This decision can be accepted as the low and intermediate nuclear waste produce limited amount of heat.

SKB presents the uniaxial compressive strength (UCS) for the two dominating rock types in the area of SFR and its extension corresponding to fracture domain FFM01in the Forsmark site investigation (SKB TR-11-04, Figure 6-1). The two rock types for which data are presented are metagranite to granodiorite (101057) and pegmatite and pegmatitic granite (101061), and for each of the two rock types the testing methods are presented. Data from point load testing at the site are omitted despite a much better sampling strategy of one sample per ten metre drill core. All presented models for the intact rock property parameters are truncated normal distributions. SKB recommends to use the mean value UCS if only one single most likely value is desired.
For pegmatite and pegmatitic granite (101061), the test data for the modelling is scattered and the number of test sample are less than for the granodiorite. Because of the large variability in the grain size and other heterogeneities for the pegmatites and granites there is a definite need for additional testing to constrain the strength and deformability. SKB suggests that larger test samples should be used in the testing of the pegmatitic rocks because of the large grain size and that the mean modelled value of UCS should be used.

The Authors also suggest that SKB performs additional tests of strength and deformability of amphibolite. The current geological model of SFR predicts that 6 % of the rock volume consists of amphibolite.

The tensile strength of the intact rock in SFR model volume has been determined with indirect tensile testing (Brazilian test) and the ratio between tensile strength and compressive strength has a range of 0.056-0.089. The presented span of ratio for five different rock types is based on a total of eleven samples. The presented data of 18 Young's modulus of intact rocks from five different rock types is another example of lack of data for determining mean and standard deviations of rock mechanics properties.

Shear testing of single rock fractures is a cumbersome and difficult testing to perform in the laboratory. During the site investigations for the spent fuel repository at Forsmark, SKB performed a relative large number of stiffness tests on small-scale fracture samples. This could be done with reliable results after a redesign of the test equipment and modifications of the data evaluation procedure. The normal and shear stiffness resulting from the testing of small samples selected for the depth interval -100 to -700 m level are presented as shown in Figure 9. There are only four tests performed at depth intervals of direct interest for stiffness determination at SFR and its planned extension. The remaining results presented are not relevant for determination of fracture stiffness for SFR and its extension.

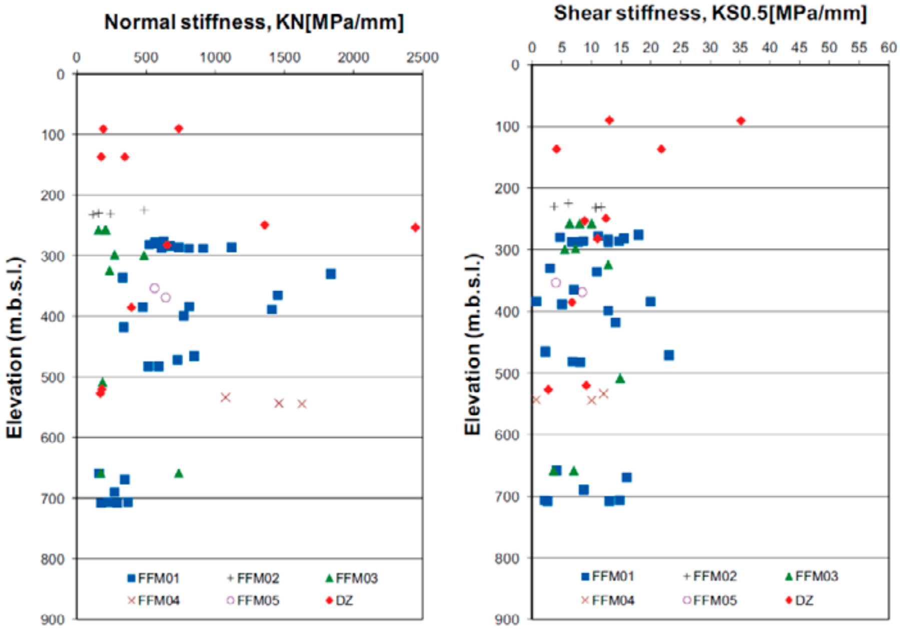


Figure 9: Results from stiffness testing on small scale fractures samples within Forsmark site investigation (Glamheden et al., 2007).

During the planning and construction of SFR in the early-mid 1980s an empirical rock mass classification according to the RMR79 system was conducted and the rock mass was classified as ‘good’ to ‘very good’ quality (SKB TR-11-04). The experience from the excavation and the results from the regular inspections of the underground excavations in SFR confirm the picture of good to very good rock conditions from a stability point of view. As also stated in the report, the exceptions to this are the conditions inside the major deformation zones where the rock quality varies over short distance and poor rock quality exists. The rock mass properties of rock domains for SFR and its planned extension are based on empirical estimates available in SKB’s SICADA database from borehole KFM11A drilled during the Forsmark site investigations. The borehole was drilled from the office area of SFR above ground at Österblänkarna with inclination -60° in direction NE and intersecting the Singö deformation zone at borehole length 498-824 m. From the core mapping of 5 m sections along this borehole and quality estimation of the rocks, an estimate of mechanical properties of the rock mass is presented in SKB TR-11-04, Table 6-8, for the depth interval 20-150 m. Data are presented for the core of the regional deformation zone and for the transition zone to major deformation zones. Also, SKB has provided a model for stiffness and strength of sub-horizontal sheet joints generated by the unloading from the sedimentary cover, which differ from regular joints in the uppermost parts of the bedrock. This is of outmost importance for the integrated conceptual understanding of the hydro-mechanical response of the overburden at SFR. The characteristics and depth of the sheet joints are new information that was not known in full at the time of constructing SFR 1 and therefore need attention and modeling when planning for SFR 3.

During the site investigations for the spent fuel repository at Forsmark, SKB made large efforts to determine the state of stress and to develop the stress measurement methods and the way of interpreting the results from the measurements. The author of the rock mechanics Chapter 6 of the report SKB TR-11-04 has brought in new data about the state of stress at Forsmark and has done a valuable and interesting compilation of old data with special relevance to the SFR area.

The major, intermediate and minor principal stress versus depth are presented in three separate figures (Figures 6-12 to 6-14) from measurements in twelve different boreholes located in the Forsmark region. There is a large spread in the data independent of depth, rock type and method used, but data show a clear increase of stress magnitude with depth. The stress magnitudes are somewhat lower in the SFR area compared to the rest of Forsmark area. The shallow stress data from the SFR area has about the same variability as other data for a particular depth but the magnitudes are lower than data coming from boreholes located west of the southern borderline in the SFR area. The rock stress model for the rock in the SFR local model volume from the ground surface down to 250 m level are presented by SKB as:

$$\sigma_1 = 5 + 0.07z$$
$$\sigma_2 = 0.07z \qquad (1)$$
$$\sigma_3 = 0.027z$$

where z is the depth in meters. The orientation of the major principal stress is estimated to be N142°E.

3.2.5. Bedrock hydrogeology

The section for bedrock hydrogeology provides a summary of the hydrogeological model for bedrock version 1.0, which is based on a comprehensive compilation, analysis and interpretation of all available hydrogeological data in the bedrock (SKB TR-11-04).

In essence, the methodology divided the subsurface into three hydraulic domains as illustrated in Figure 7-1 in SKB site description report where:

- The Hydraulic Conductor Domain (HCD) represents deterministically modelled deformation zones
- The Hydraulic Rock mass Domain (HRD) represents the less fractured rock mass volumes in between the deformation zones, and
- The Hydraulic Soil Domain (HSD) represents the regolith on top of the bedrock.

The most significant component of the bedrock hydrogeology relevant to this Initial Review in the context of rock engineering and engineering geology is the measurement of inflow in the SFR facility carried out regularly since January 1988. The total inflow in 1988 was about 720 l/min, and this has been steadily decreased to about 285 l/min by 2010 as shown in Figure 3. Possible explanation was the increasing effective normal stress, two phase flow and chemical precipitation. More analysis was introduced in the Chapter 9 “Current understanding of the site”. One of the findings was that the effective normal stress increase can cause the decrease of fracture aperture. It is also acknowledged by SKB that it is a remaining key uncertainties whether the inflow or aperture will continue to decrease, or increase again, and whether it is reversible or irreversible. These are difficult questions involving various factors and SKB has not given a firm answer to these. The

Authors of this review report also agree that it is not straightforward to fully explain these questions. Nonetheless, continued monitoring and combined modelling are needed in order to improve the understanding of the inflow observations. For example, more integration with rock mechanics can provide more explanation on the mechanisms of effective normal stress increase in conjunction with DFN modelling and non-linear fracture stiffness.

Another interesting observation is that the difference in transmissivity between the gently and steeply dipping fractures measured by PFL (Posiva Flow Log) method appears to be correlated to the rock stress model as shown in Figure **10**. As vertical stress is much lower than the two horizontal stresses, the horizontal fractures apparently show larger transmissivity because they are more open that steeply dipping fractures. This is a very interesting observation, and improved understanding can be achieved by combining hydraulic and mechanical modelling, which can also reveal the influence of stress concentration around the rock cavern with consideration of fracture and principal stress orientations.

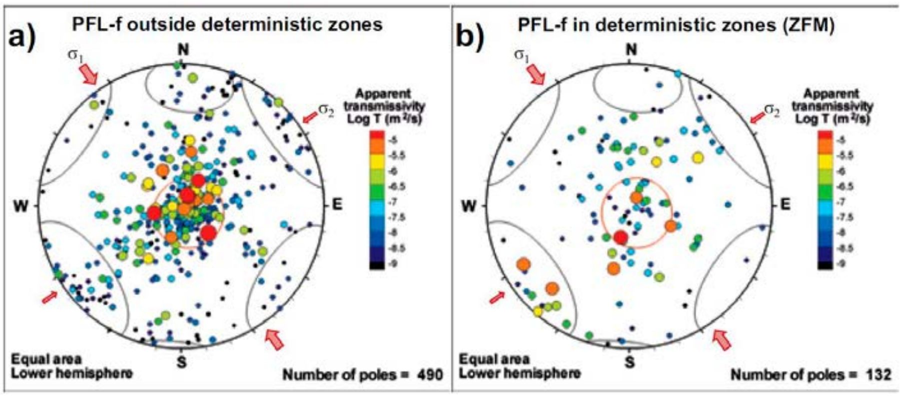


Figure 10: Orientations of fractures detected by PFL (Posiva Flow Log) method with respect to stress field. a) outside deterministic deformation zones and b) inside deterministic zones. The horizontal principal stress orientations is shown by red arrows (SKB TR-11-04).

3.2.6. Summary

- SKB has conducted and presented an ambitious and comprehensive site characterization and site descriptive model for the planned extension of the existing final repository for low and intermediate radioactive waste SFR 1.
- SKB has not delivered an explanation about the selection of size and location of the different site descriptive models used for the safety analysis of SFR 1 and its extension. From existing information about geophysics, bedrock geology and knowledge about existing major deformation zones, a location of the extension of SFR towards NE and close to the border of the regional model could be an alternative.
- The planned extension SFR 3 lies in a tectonic block that is bounded by two broad belts consisting of ductile and brittle deformation zones. The bedrock in the selected area is highly heterogeneous and the geological structures are complex. There are not enough data collected to fully

characterize the rock mechanics properties of the bedrock and deformation zones at the SFR site and the extension.

- The sheet joints and their flow and mechanical characteristics in the uppermost part of the bedrock are the most uncertain components in the local and regional model for the extension of SFR. The uncertainty exists whereas the sheet joint structures will reach the roof of the rock chambers in the extension part of SFR. The existence of sheet join to the depth of the vault in SFR 3 is of importance for the geometry and stability of the roof of the vaults.

- There is a large spread in the magnitude of the measured stress data independent of depth, rock type and method used, but there is a clear increase of stress magnitude with depth. The stress magnitudes versus depth are somewhat lover in the SFR area compared to the rest of the Forsmark area.

- Measurement of inflow data in the SFR facility is precious in understanding the nature of flow field near SFR. Possible correlation between stress field and fracture transmissivity shows that there is a possible influence of the stress field on the flow fields. Coupled hydro-mechanical analysis with explicit modelling of mechanical stress and deformation in fractured rock geometry could improve the understanding of the coupled flow and stress field.

3.3. Data report for the safety assessment SR-PSU (SKB TR-14-10)

3.3.1. Introduction

This report presents the most important data and their quality for the long-term safety assessment SR-PSU of the extension of SFR. The presented data are connected to the safety functions applied in SR-PSU. The data report for the safety assessment SR-PSU has the objective to perform data qualification, data uncertainty and variability and traceability for various subject areas used in the safety assessment. In addition the scientific adequacy and quality of the data are of importance for the applied methodology and for identifying and quantifying data for the safety assessment.

3.3.2. Methodology for identifying and quantifying data

SKB is presenting a scheme of preparing and reviewing the data report for safety assessment (Figure 11). It is not clear from the text and list of references if the suggested procedure is in accordance with international recommendations and standards or it is fully developed by SKB. The procedure follows four stages and all together 12 steps for formulating a subject area. Each of the twelve steps is well written and gives clear instructions to the team developing the data report. Sections 2.1.6 - 2.1.9 about conceptual uncertainty, representativity, variability and correlation are of good quality and the list of questions provided for the individual sections are relevant and well formulated. To make the final assessment for choosing the data, the representative person of data supply and the SR-PSU team will meet for a data qualification meeting where the formal decision is made about the data to be used for the SR--PSU modelling. This finalizes the third stage of the outline. This stage is followed by an additional review "according to standard procedures" as stated by SKB in Figure 2-1 in the report. The Authors of this review report believe that this procedure is acceptable for data assessment and modelling according to SR-PSU.

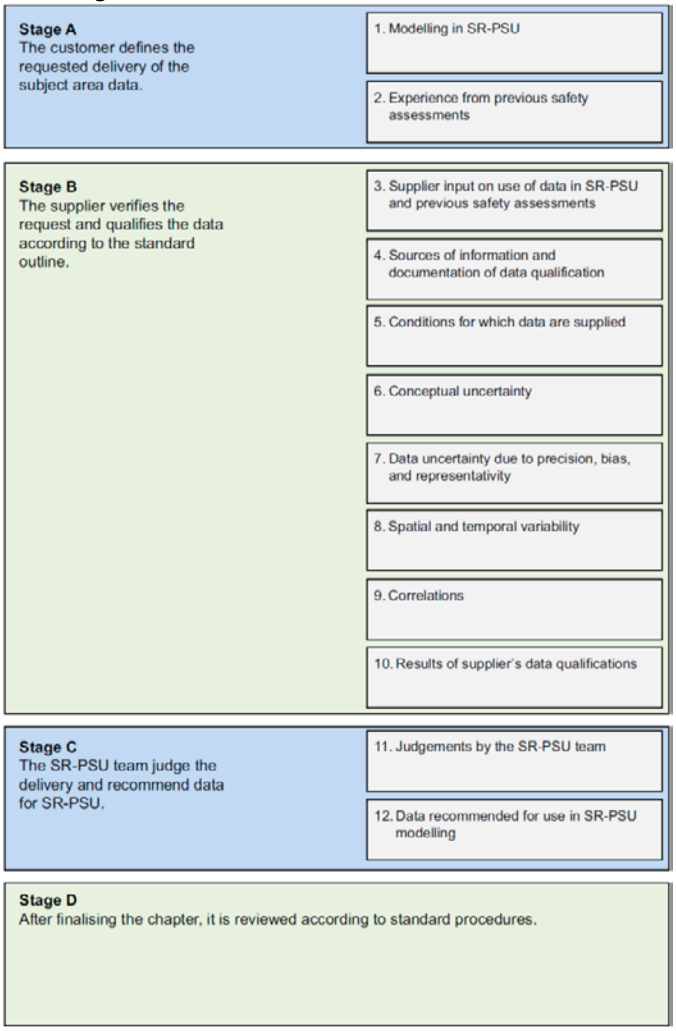


Figure 11: Stages of writing and reviewing the Data report. The standard outline for assessing data for a subject area is shown in the grey boxes (Data Report, SKB TR-14-10).

3.3.3. Hydraulic pressure field in the SFR local domain

Chapter 11 of the Data report deals with the data needed for analysing the effect of changing magnitude of the groundwater gradient over time due to shoreline evolution and climate change. It is explained by SKB that the current gradient is directed upwards when the repository is below the sea floor but after 1,000or 2,000 years the gradient is expected to increase and become more horizontal, which is controlled by the local topography.

The data requested for modelling three bedrock cases are: dynamic pressure, groundwater velocity and rock permeability field. The SR-PSU modelling activities is conducted for the Global Warming climate case and the periglacial climate with a shallow permafrost depth. The assessment is used to extract requested data for the temperate and periglacial climate domains and the three different bedrock models. Three different bedrock cases account for the spatial and temporal variability. A base case bedrock case, one low-flow bedrock case and one high-flow bedrock case are considered. The temporal variability of data is covered by using three different shoreline positions for the temperate climate domain. The result of the data supplied to SR-PSU team are 19 data files of which 17 are delivered files of the temperate climate domain and 2 delivered files are for the periglacial climate domain.

In the report there is a lack of information about the contents and modelling conditions of the presented data files in Table 11-2 (SKB TR-14-10). This information needs to be provided in order to judge the results based on the presented data files.

3.3.4. Shoreline evolution

The shoreline at Forsmark varies in time due to changes in the relative sea-level, which is an effect of eustatic changes from the spatial variation of ocean water and isostatic changes from glacial rebound (Figure 12). It is stated in the SKB report that the future shore-level evolution at Forsmark has to be provided for each of the suggested climate cases suggested in SKB Climate report. The shoreline data are requested for the time period from the Weichselian deglaciation of Forsmark to 100,000 years into the future. Modelling of the evolution of the relative shorelevel is conducted for four different climate models, namely the Global Warming, early periglacial climate case, extended Global Warming and Weichselian glacial cycle climate case. Figures showing the relative shorelevel evolution data versus time for the four different climate cases, which are extracted from the SKB Climate report 2014 (SKB TR-13-05) and reproduced in the SKB Data report for the safety assessment SR-PSU. The evolution of relative shorelevel data presented in Figure12-1 and 12-2 in SKB Data report are recommended by the SR-PSU team for use in SR-PSU modelling of shorelevel evolution.

The Authors of this review report believe that the selected approach and shoreline data are appropriately presented to be used for the long-term safety analysis in SR-PSU.

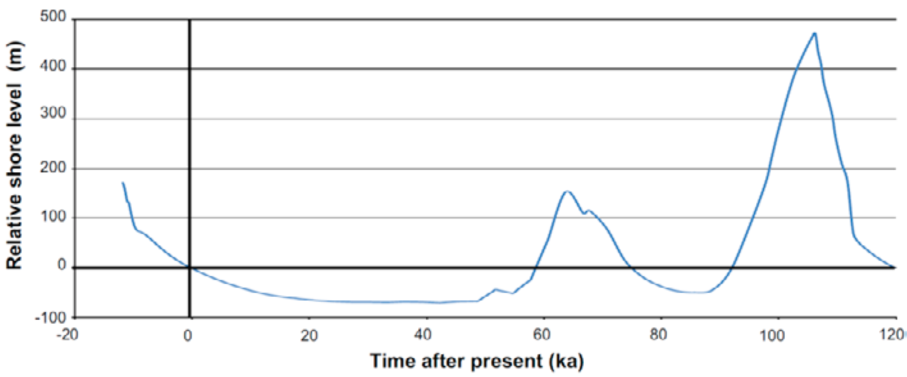


Figure 12: Shore-level evolution data for the period 10,800 years before present (8800 BC) to 120,000 years after present for the Weichselian glacial cycle climate case (Data Report, SKB TR-14-10).

3.3.5. Summary

- The individual steps of the procedure and the overall structure for data assessment and modelling according to SR-PSU are acceptable.
- In the report there is a lack of information about the contents and modelling conditions of the presented data files in Table 11-2 (SKB TR-14-10). This information needs to be provided in order to judge the results of the presented data files.
- The evolution of relative shore level data presented in SKB Data report are recommended by the SR-PSU team for use in SR-PSU modelling of shore-level evolution. The selected approach and shoreline data are appropriate for the long-term safety analysis in SR-PSU.

3.4. FEP report for the safety assessment SR-PSU(SKB TR-14-07)

3.4.1. Introduction

For the analysis of the post-closure radiation safety of the low and intermediate level waste in SFR, SKB has presented a report describing the processing and analysis of features, events and processes, so called FEPs. This report is one of the main reports for the SR-PSU safety assessment for the extension of the SFR repository. The SR-PSU FEP catalogue together with the two most recent catalogues SR-Site FEP and SR-Can FEP catalogue are all parts of SKB's FEP database.

According to the SKB report, the contents of the catalogue for the SFR extension have been checked and audited against version 2.1 of the NEA international FEP database and against FEPs developed from two low and intermediate level repository projects in Finland and Japan, respectively. This international auditing procedure and documentation certainly enhance the quality and completeness of the SR-PSU FEP list. The completeness, quality and adjustment of SR-PSU to the previous developed FEP lists in SKB's FEP database is governed by having the same authors and coordinators for the work (i.e. Kristina Skagius and Maria Lindgren). In the routines for management of the FEP database only one person has been allowed to make modifications to the structure and content of the database (i.e. Kristina Skagius).

SKB's long experience in working with development, classification and auditing of FEPs, on one side, and the thorough comparison with the content of NEA's FEP database and its long list of included international projects (see Table 3-1 of SKB-TR-14-07), on the other side, give the best guarantee for a high quality and completeness of the presented FEP catalogue. Also, SKB has been active in developing new methods to develop FEP-lists, i.e. the interaction matrix approach (Figure 13).

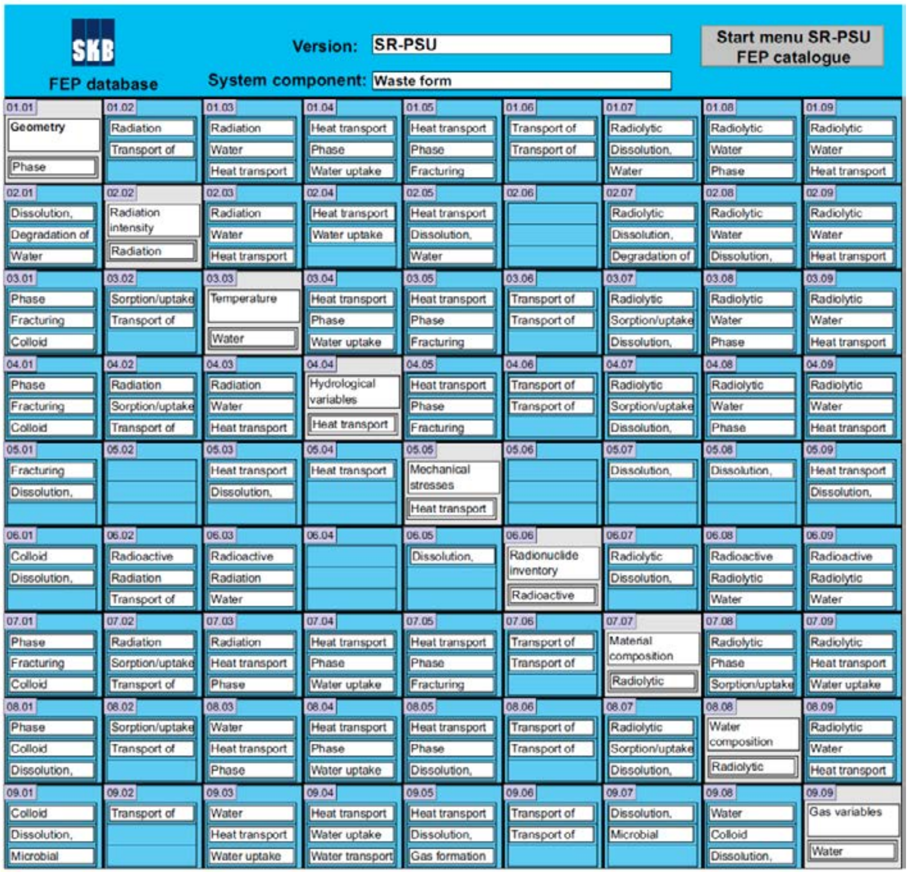


Figure 13: An example of interaction matrix for the waste form (FEP Report, SKB TR-14-07).

3.4.2. Large-scale geological FEPs

In Chapter 4 on further processing of FEPs, SKB describes the different procedures applied for the post-processing derived from screening, classification and auditing the FEPs. The internal processes of the waste in the vaults and their barriers are analysed followed by the FEPs describing the initial state, external factors, the biosphere FEPs and finally methodology issues. In Section 4.3.2 on large-scale geological processes and effects, SKB states that in SR-Site two FEPs belonging to the group "External factors" were defined to cover large-scale geological processes namely "Mechanical evolution of the Shield (LSGe01)" and "Earthquakes (LSGe02)". These two large FEPs are also included in SR-PSU since both the repository for spent fuel and SFR are planned to be located in Forsmark.

The way SKB is handling the NEA Project FEPs in the SR-PSU Project for External factors are listed in Appendix 13 of the SR-PSU FEP report. Table A13-8 of Appendix 13 presents the SR-PSU FEP LSGe01 Mechanical evolution of the Shield. The table contains the relevant NEA FEPs relevant for mechanical evolution of the Shield followed by a text explaining why the specific FEP is not specifically addressed in the SR-PSU Geosphere Process Report (SKB TR-10-48) because the SR-Site descriptions is applicable for the Forsmark site including SFR. For each of the 14 listed NEA FEPs except one, W 1.010 on formation of new faults, SKB is referring to different sections in the report Geosphere Process Report for the safety assessment SR-Site. SKB's FEP list for SR-PSU does not specifically consider the effect of transmissivity changes in the rock mass at SFR caused by the thermal expansion of the rock mass in the repository of the spent nuclear fuel.

Recent studies by Min et al. (2013, 2015) has shown that the thermal expansion can cause shear slip along pre-existing fractures and deformation zones and result in changes of the transmissivity. The final extension of shear slip of fractures and deformation zones around the repository for spent fuel at Forsmark is not known at present. The distance from the eastern part of the repository for spent fuel to the border of the planned extension of SFR is about 1.5 km. The risk of transmissivity changes of the rock mass in the vicinity of the extension of SFR from the heat load of the repository of spent fuel is a scenario that needs to be formulated and presented as a FEP and followed by thermo-mechanical and hydro-mechanical modelling. Expressed in terms of interaction matrix methodology the process is a thermo-mechanical evolution of the shield rock that is caused by the heat from the spent fuel and the effect is thermo-shearing that can cause transmissivity changes in the rock mass around SFR.

Because of thermal loading from the repository of spent fuel, the NEA FEPs K 9.06 on stress changes and hydrogeological effect, J.4.2.06 on faulting and J.4.2.07 on thermo-hydro-mechanical effects are applicable to the process of thermo-shearing and related transmissivity change. These NEA FEPs belong to SR-PSU FEP Ge03 Groundwater flow.

As stated by SKB, large-scale geological processes are not specifically addressed in SR-PSU because the SR-Site descriptions are applicable to the Forsmark site, including SFR. Large-scale geological processes and their effect belong to the NEA FEPs on earthquakes, seismicity, seismic activity, faulting and hydrogeological response to earthquakes. These large-scale geological processes and their NEA FEPs are collected in the SR-PSU FEP LSGe02 on earthquakes, see Table A13-9 in SKB TR-10-48.

The heating from the spent fuel can cause thermal stresses and earthquakes from the release of the strain energy of critically stressed deformation zones or long fractures. The thermal stresses and the stress relieve causing earthquakes can take place on some of the critically located deformation zones within the area of the planned extension of the SFR or its vicinity and affect the stability and long-term integrity of the engineered barriers and rock vaults with the waste. This type of earthquakes is not of geological origin in the sense that it is generated by geological processes like tectonics, glaciation, uplift etc. Instead it is generated or induced by the heating at the spent fuel repository and therefore belongs to a new group of external factors that needs to be developed and described by SKB.

3.4.3. Concrete degradation

In recent years there has been an accelerating degradation of the concrete and reinforcement structures in several areas and vaults of the existing SFR 1. SKB has started to repair the concrete, e.g. for the structures of the concrete barrier in the existing BMA. A description of the present situation regarding degradation of the concrete and the formation of fractures is described in the SKB report about Data for the safety assessment (SKB TR-14-10, Chapter 10). Several SR-PSU FEPs are related to degradation of concrete. The same or similar FEPs related to concrete degradation are also defined for the BTFs, the silo barriers, and the BRTs. For BLAs, no concrete barrier exist except the concrete floor and therefore degradation of rock bolts, reinforcement and concrete are covered by one and the same FEP BLABa13 listed in Table A10 through A12 and presented in Appendix 10. A similar approach is applied for the FEPs related to plugs and other closure components.

This approach to separate the cause and effect for different components of concrete structures can be accepted as these structures contain several different components and materials.

3.4.4. Comments to FEPs linked to PSU Geosphere processes

In Appendix 12 are listed the NEA Project FEPs that are linked to PSU Geosphere processes. FEP Ge03 on groundwater flow is a very large SR-PSU FEP with ca 120 individual FEPs. One of the FEPs, K9.06 on stress changes and hydrogeological effect, is applicable to the effect of transmissivity changes in the rock mass at SFR caused by the thermal expansion of the rock mass in the nearby repository of the spent nuclear fuel. According to SKB, this FEP is addressed in the process report but not considered for additional modelling. The only way to know if heating of the repository for spent fuel can cause stress changes at the SFR site and its vicinity that can lead to hydrogeological effects, is to conduct 3D thermo-hydro-mechanical modelling.

FEPs Ge05 through Ge07 dealing with rock mechanics (deformation, strength and fracturing) have been given the comment “All relevant aspects addressed”. The reader of the report wants to know what aspects have been addresses and where to find the information.

3.4.5. Summary

- The international auditing procedure and documentation used by SKB certainly enhance the quality and completeness of the presented SR-PSU FEP list.

- The risk of transmissivity changes from shear slip of the rock mass in the vicinity of the extension of SFR due to the heat generated by the planned repository of spent fuel is a scenario that needs to be formulated and presented as a FEP. Thermo-mechanical and hydro-mechanical modelling of transmissivity changes from shear slip is recommended.

- Heat from the nearby spent fuel repository could cause thermal stresses and earthquake due to the release of the strain energy of critically stressed deformation zones or long fractures. The stress relieve causing earthquakes could take place at some of the critically located deformation zones within the area of the planned extension of the SFR or its vicinity and cause transmissivity change in the rock and/or damage the vaults.

- The approach to separate the cause from the effect for the concrete structures in SFR can be accepted as these structures contain several different components and materials.

3.5. Initial state report for the safety assessment SR-PSU(SKB TR-14-02)

3.5.1. Introduction

The Initial State Report compiles information on the initial state of the waste and repository for the long-term safety of SFR. The initial state is defined as the expected state of the repository and its environs immediately after the closure, which is estimated to happen in year 2075 (Figure 14). The initial state of the repository is based on verified and documented properties of the wastes and the repository components plus an assessment of changes in these properties until the time of closure. When sealing and closure of vaults and tunnels are completed by 2075, no further actions will be needed to support the function of the passive underground repository. This initial state report is part of Step 2 for the long-term safety assessment (see Figure 4). This report describes waste acceptance criteria, reference waste inventory, repository reference design, as well as control and inspection process used to secure an appropriate initial state of SFR, which is an important base for the safety report covering the construction and operation of the SFR facility.

The present review report covers initial state of mainly repository silo and vaults other than the initial state of the waste itself.

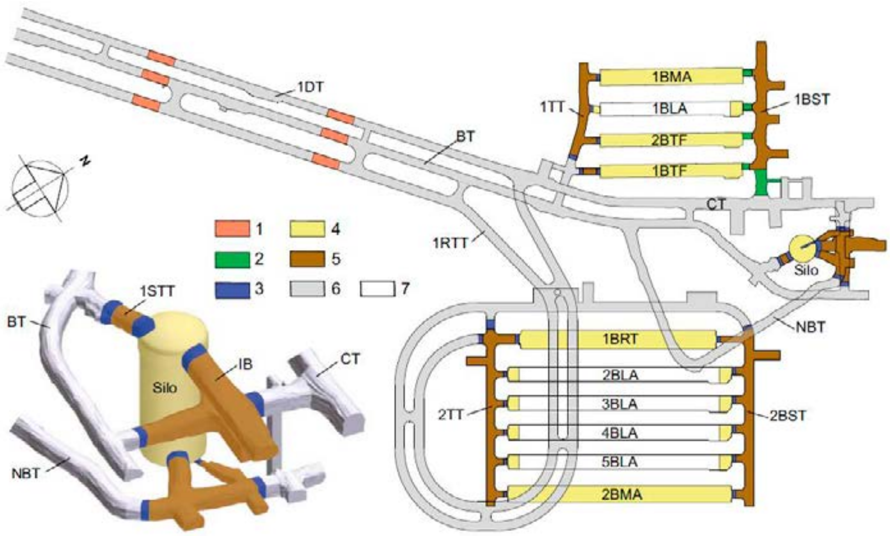


Figure 14: Overview of SFR after closure expected in 2075 with detailed view of the silo. Legend indicate, 1) plugs in access tunnels, 2) transition material, 3) mechanical plug of concrete, 4) backfill material of macadam, 5) hydraulically tight section of bentonite, 6) backfill material in access tunnels and tunnel system, 7) openings without backfill (Initial state report, SKB TR-14-02).

3.5.2. Mechanical stability of rock vaults and Silo

SKB states that the mechanical stability of rock vaults and silo is increased by the shotcrete on the rock walls and/or the buffer material between concrete structure and rock wall, which is the case for the silo. However, there are no quantitative analyses to demonstrate this, and no references are given to earlier studies and reports. The initial state report did introduce comparison of measured and modelled silo settlement as shown in Figure 15.

However, SKB gives no explanation about how the modelling is conducted and reference is not given. One can wonder why monitoring data were presented only by 2010. More detailed and elaborate analysis for the silo will be desirable given the size and importance of the structure. If possible, this stability analysis can include the inflow prediction as well in order to prove the level of understanding. Upgraded modelling of the silo is recommended especially because most of modelling was conducted over thirty years ago and recent modelling work is very limited (Carlsson and Hedman, 1986; Carlsson and Christiansson, 1986; Larsson and Christiansson 1986; Stille and Fredriksson 1988, Björk and Malmström, 2004).

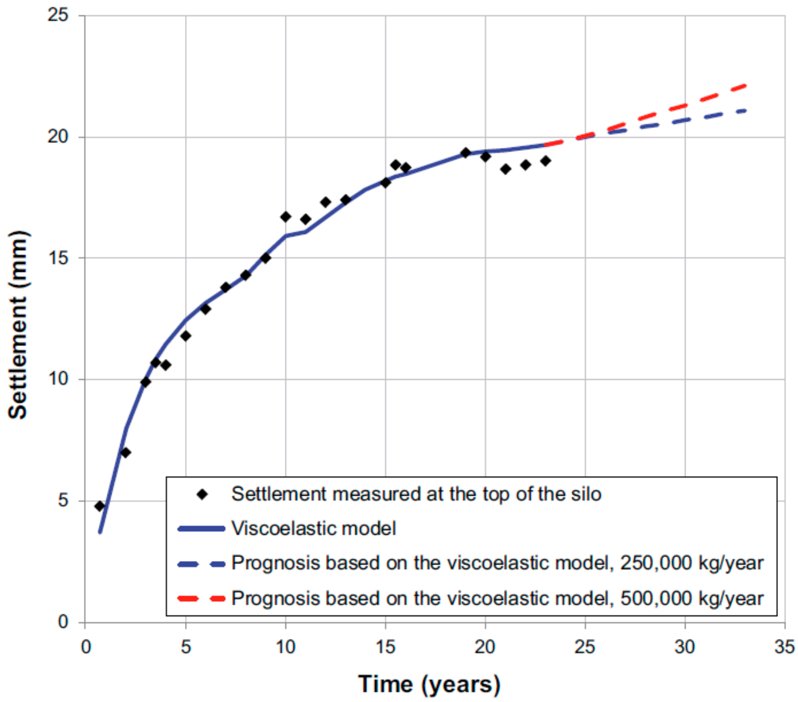


Figure 15: Measured settlements of silo in SFR 1 and prediction by viscoelastic model (Figure 7-5, Initial state report, SKB TR-14-02).

3.5.3. Mechanical and hydraulic interaction between existing SFR 1 and SFR 3

Not much information is given in terms of the distance between the planned SFR 3 vaults and existing SFR 1 facilities. Mechanical and hydraulic influences of the rock mass are expected and explanation needs to be given on how this is considered.

3.5.4. Sealing of boreholes of the site investigation

Sealing of boreholes has to be conducted with close reference to the observations of fluid conducting fractures and borehole breakout in the existing investigation borehole (e.g., Niesen and Ringgaard, 2009).

On page 97 of SKB TR-14-02, it is stated that some boreholes sealed after the investigations for SFR 1 may not fulfil the current requirements. Fuller explanation needs to be given on this remark. A complete inventory of the investigation boreholes and their conditions may be desirable.

3.5.5. Summary

- Complementary information in regards to the mechanical stability of rock vaults and silo is necessary.
- Hydro-mechanical interactions between existing and new rock vaults have to be elaborated and presented.

3.6. Model summary report for the safety assessment SR-PSU (SKB TR-14-11)

3.6.1. Introduction

This report describes the computer codes used to carry out the modelling studies for the safety assessment SR-PSU, and the documentation and quality assurance (QA) procedures associated with each code. An assessment Model Flowchart (AMF) is introduced for illustrating how the modelling tasks in the assessment are connected. The report intends to demonstrate that the codes are suitable for their purpose, has been used properly, and the code development process has followed appropriate procedure and producing accurate results. This report also describes how data are transferred between the different computational tasks.

The current review report provides observation focusing on the computer codes 3DEC, ADINA and Comsol Multiphysics, which are related to rock engineering and engineering geology.

3.6.2. Quality assurance principles on used computer codes

SKB divides the computer codes into the following four categories:

- Category 1: commercial system software such as operating systems, compilers and database software.
- Category 2: Software conducting straight-forward calculations such as unit conversion and pre- and post- processing.
- Category 3: wide-spread commercial and open sources codes.
- Category 4: modified commercial codes (a), and codes specifically designed for the safety assessment (b).

Codes in Category 1 and 2 are not included in the code assessment assuming that their calculations are correct. Given that these codes are widely accepted and easy-to-use, the Authors believe this SKB's decision is appropriate.

Codes in Category 3 are not included in the code assessment as well because these codes are considered to be sufficiently well tested, and widely used.

Codes in Category 4a are to be verified only for the added functionality; codes in Category 4b are to be verified more extensively because of smaller base of applications.

The Authors argue that more extensive verification principle should apply to Category 3 and Category 4a. Nowadays, state-of-the-art computers codes dominant in their respective fields are often very complex, and abuse or misuse of these computer codes are problematic. Even if a particular computer code itself can correctly solve a problem, e.g. a partial differential equation, the computer code can produce erroneous results when the user does not handle the codes properly. According to the Authors' experience, unfortunately, this happens quite often.. Therefore, the verification of numerical analyses should be composed of two aspects: 1) whether computer codes solve the given problem correctly, 2) whether the user is applying the code properly so that the correct results are ensured. In this regards, verification of Category 3 codes should be also provided systematically. This will show that numerical codes are properly handled by users. This verification can be easily performed by comparison against analytical solution or other numerical codes. The credibility of the results shouldn't be judged only based on which computer code was adopted.

3.6.3. More information about the development process and verification for 3DEC, ADINA and Comsol Multiphysics

SKB specified four basic requirements for the quality assurance of each code:

- The code is shown to be suitable for its purpose
- The code has been used properly
- The code development process has followed appropriate procedures and that the code produces accurate results
- A description of how data are transferred between the different computational tasks is provided.

Based on above-mentioned four requirements, six headings, namely, 'introduction', 'suitability of code', 'usage of the code', development process and verification', 'handling of input data, computational results and scripts', and 'rationale for using the code in the assessment' have been used to describe each code.

In line with above comment regarding more robust verification for Category 3 computer codes, the Authors judge that the information provided about 'development process and verification' for 3DEC and Comsol Multiphysics is not sufficient.

It is stated in the bottom of page 19 in SKB TR-14-11 that verification documentation can be found on the website http://www.itascacg.com/software/3dec. However, this website contains only market orientated information without robust verifications. The Authors understand that more robust verification is available in form of a manual. In order to confirm that the code is verified, SKB should either provide verification cases, which can be taken from manual, or provide the manual to SSM. Otherwise, there is no way for SSM to confirm and evaluate the code verification.

This comment applied to Comsol Multiphysics as well. Two sentences given for section ‘development process and verification’ for Comsol Multiphysics are not really sufficient to confirm that Comsol Multiphysics produces accurate results for safety assessment. In particular, Comsol Multiphysics is a general purpose computer codes, and more systematic verification cases suitable for hydrology problem should have been provided to SSM. The superficial presentation of verification of the applied codes hinders a proper future traceability of the applied codes.

The same comment also applies to other codes such as ADINA code and more traceable and transparent information need to be provided.

3.6.4. Other minor comments

The issue of compatibility of the models to different versions of the codes is important, especially during the review process and during the time of validity of the present Safety Case. Each code will undergo continuous development, and very often, newer versions are not compatible with older version, if not the immediate close version. In such case, it happens that old modelling files cannot be accessed with the new version. Although it may not be the responsibility of SKB to provide all the traceable code record, the Authors of this review report would like to point out that this issue is an important consideration for safety assessment especially in the longer term.

3.6.5. Summary

- In general, this report needs to be complemented with additional information. More robust verification even with commercially available codes has to be provided because misuse or abuse by users is also a concern.
- Furthermore, information about verification has to be properly given for 3DEC and Comsol Multiphysics. The code-specific comments concerns only 3DEC, ADINA and Comsol Multiphysics, on which the Authors of this review report are familiar with.

3.7. Input data report for the safety assessment(SKB TR-14-12)

This report provides data or references to where data used in the assessment of the long-term radiation safety of the low-and intermediate level waste repository SFR can be found. The report forms part of the SR-PSU safety assessment, which supports the application for a license to extend SFR.

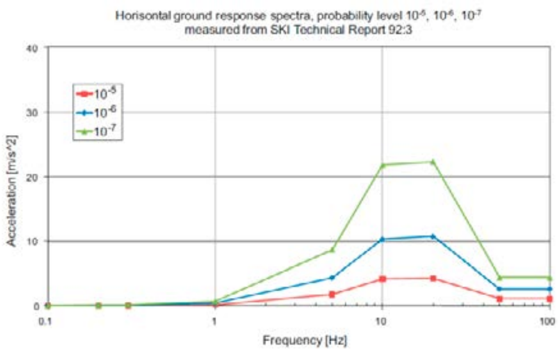
No particular review comments in relation to rock engineering and engineering geology are given about this report.

3.8. A seismic evaluation of SFR. Analysis of the Silo structure for earthquake load (SKB R-13-52)

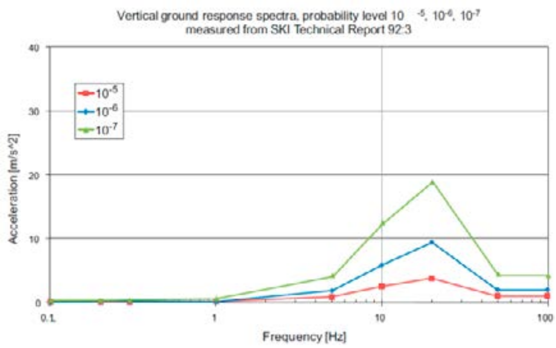
3.8.1. Introduction

This report aims to present an estimate of the SFR Silo structure capacity to withstand the load effects that arise in the event of an earthquake. The earthquake loads are classified according to their annual exceeding frequency level indicating the possibility of a seismic event with a certain magnitude to occur within a certain period of time and within a certain distance. The SFR Silo was analysed using the finite element program ADINA for earthquake loads with annual frequency of 10^{-5}, 10^{-6} and 10^{-7}(Figure 16) based on SKI's work (1992). A lower probability stands for a more powerful earthquake. The possible deterioration of the concrete material in the Silo was not considered, but the steel reinforcement was considered to be severely corroded leading to a negligible load bearing capacity.

It is noted that the whole analysis was conducted only on the concrete structure without specific consideration of the underground rock structure (Figure 17). Important conclusion from this report is that the SFR Silo structure will maintain its integrity under the loading from an earthquake with an annual exceeding frequency of 10^{-5}. However, with annual probability level of 10^{-6} and 10^{-7}, the structural integrity cannot be guaranteed because extensive cracking in the outer wall, tension in the casting joint between the slabs and outer wall and inner walls experiencing stresses significantly above the tensile limit strength can be expected.



(a)



(b)

Figure 16: Ground response spectra used in the SKB document (SKB R-13-52). (a) horizontal, (b) vertical. All spectra have 4 % damping.

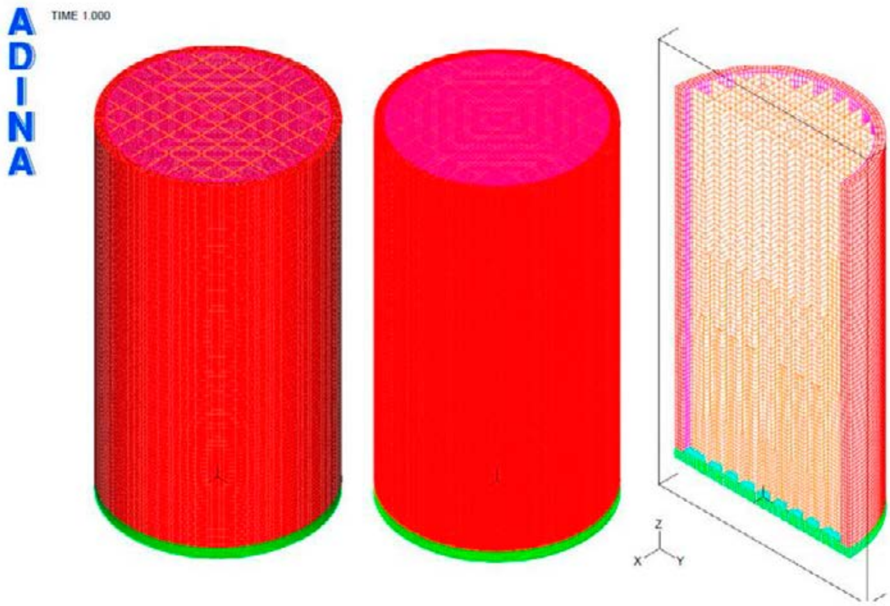


Figure 17: Finite element model used in SKB report (SKB R-13-52). Geometry overview (left), full element mesh (centre), and section through the centre of the model (right). The rock mass surrounding the Silo was not modelled in this analysis.

3.8.2. Earthquake analysis of underground rock structures

As this review report is focused on rock engineering and engineering geology issues, the comment on the structural analysis on concrete structure is limited. Instead, it is emphasized that more detailed systematic earthquake analysis is necessary for underground rock chambers both in SFR 1 and SFR 3. The distinctive insight that can be gained from an earthquake analysis of the underground rock structure is the role of numerous fractures existing in the rock mass. Rock fracture can slide due to earthquakes and this will have impact on the stability. Also sliding fractures can induce dilation resulting in larger transmissivity to fluid flow along the fractures. It is also important to conduct earthquake analysis of concrete structures that are located in fractured rock mass. Earthquake can affect the concrete structure through cavern stability and fracture and block displacement.

A recent study coordinated by Ontario Power Generation in Canada for geologic repository for low and intermediate waste shows that an extensive sensitivity study considering rock fractures and rock degradation can give an insight into the long-term mechanical behaviour of a rock cavern affected by an earthquake (Itasca, 2011).

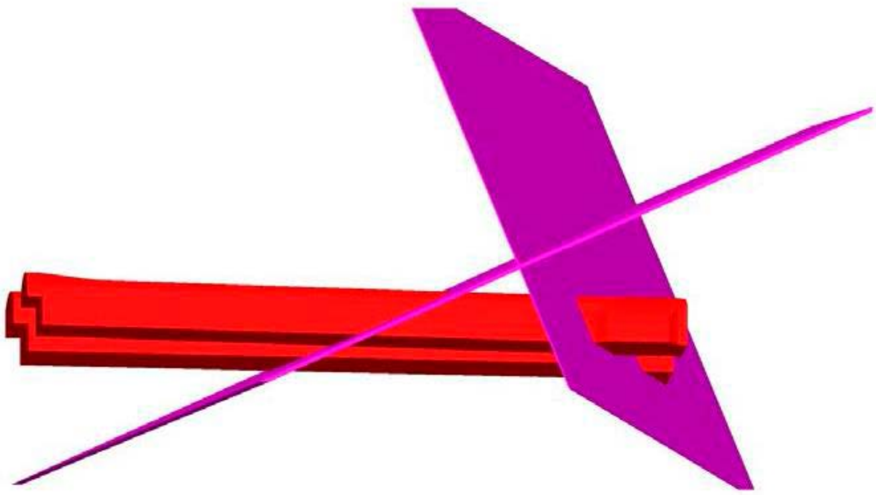
3.8.3. Summary

- This report provides a useful conclusion for the Silo concrete structure in terms of its structural integrity against earthquake loading. However, more complete earthquake analysis considering the response of and loading from the rock chamber constructed within a fractured rock mass is necessary.

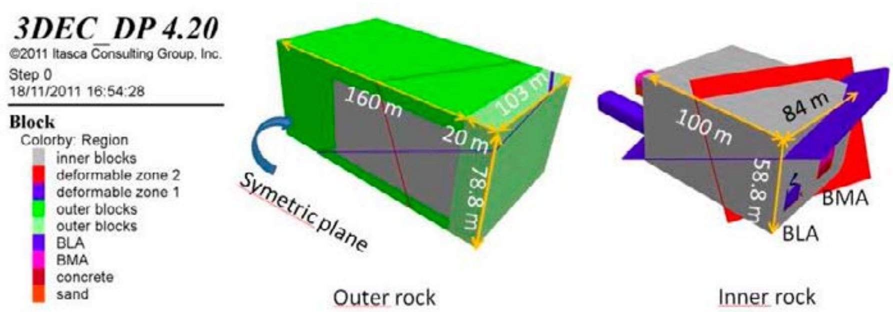
3.9. Long term stability of rock caverns BMA and BLA of SFR, Forsmark (SKB R-13-53)

3.9.1. Introduction

The objective of this report is to analyse a long-term risk for an ongoing loosening of the rock mass due to degradation and weathering of the rock mass adjacent to the walls of the rock caverns, and long term stability of the pillar between the repository rooms BMA and BLA in SFR 1. The report describes a study of long-term stability of the caverns BMA, which is modelled as left empty, and BLA, which is considered backfilled with sand, using three dimensional discrete element code 3DEC (Itasca, 2011). The study was limited to 100 m along the two caverns within a section intercepted by two minor deformation zones (Figure 18). A random fracture generator has been used to construct the 3DEC models to capture the mapped fracture statistics. The key modelling method in SKB's study is the consideration of degradation of the rock mass adjacent to the caverns' walls by successively reducing the fracture strength. Although there is no mention about the time span over which the degradation in this modelling exercise occurs, this can be considered any arbitrary time scale when the frictional properties become small enough.



(a)



(b)

Figure 18: Models for stability analysis using numerical model (SKB R-13-53). (a) Geometry of two deformation zones, (b) dimensions of numerical models.

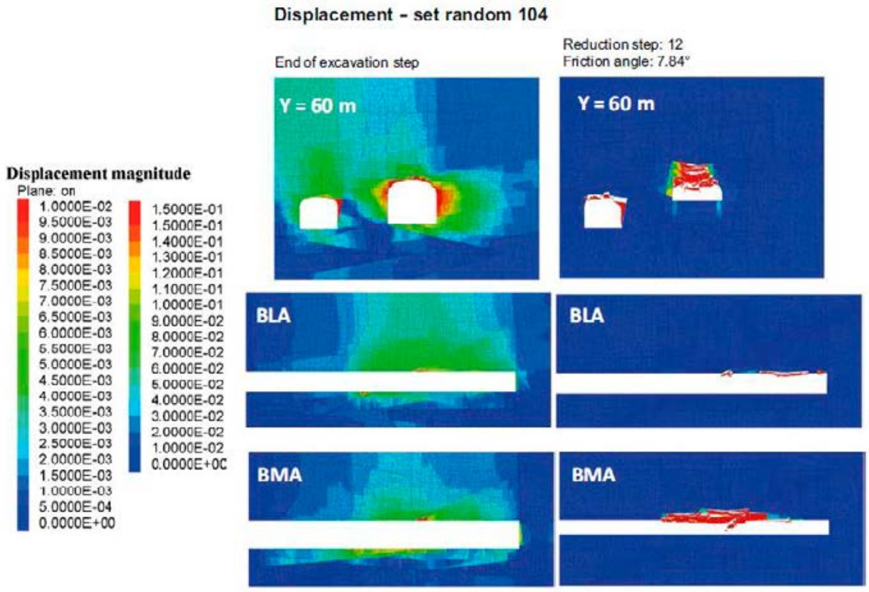


Figure 19: Contour plots of the displacement (in metres) across vertical sections after excavation (left) and after the critical fracture friction angle 7.84°has been reached (right) (SKB R-13-53).

The results show that the caverns and the pillar between them remain stable without rock reinforcement. In some modelling cases, it was shown that blocks can fall into the caverns for the cases with low friction angles (Figure 19). In one modelling case, which is arguably fairly conservative with widening zones of friction angles lower than 5.7°, the loosening of rock mass reaches a height of up to 34 m above the cavern's roof, and the deformation at the rock surface at that position is about 3.5 cm. The general conclusion of this SKB's report is that the caverns remain stable for the assumed present-day fracture properties without rock reinforcement. However, instability and rock fall can be observed with reduced fracture friction angles to values as low as 5.7° and 8.7°, which are claimed to be unrealistically low.

The review in this report has been conducted in view of the legitimacy of the choice of input parameters, relevance to the SFR-PSU safety analysis, and comprehensiveness of numerical analysis.

3.9.2. Systematic long-term mechanical analysis for SFR 1 and SFR3

This study only considered two rock vaults (1 BLA and 1 BMA) assuming the other two vaults symmetrically placed in the existing SFR1 facility. It appears that this is the only SKB report that conducted the mechanical stability of rock chambers and vaults. The stability of the Silo can potentially pose a greater problem due to its large size. Furthermore, since it is the extension of SFR that is being reviewed rather than continuation of SFR 1, there must be extensive stability analysis ensuring that the current design of SFR 3 is safe and no significant rock fall or loosening of adjacent rock block is anticipated.

Furthermore, it is reported that significant rock fall was observed with about 7.5 m of overbreak during the construction of the outlet tunnel of reactor Forsmark 3 passing Singö deformation zone (Carlsson and Christiansson, 2007). More comprehensive plan and analysis to ensure the stability of SFR 3 considering large major deformation zone is needed. Otherwise, there must be compelling reasons addressing that the current analysis of BLA and BMA in SFR1 is the most critical and sufficient to account for the mechanical stability of the chambers and Silo in SFR 1 and SFR 3.

Another important aspect is the direction of the waste vaults in SFR 3. According to the layout (Figure 1), the long axis of the vaults are directed toward North-East, which is almost perpendicular to the direction of major horizontal stress, which is determined to be 142°from North. There must be compelling argument for this decision. When designing shallow underground structures the long axis of the chamber used to be oriented perpendicular to the major principal stress. The extension of SFR is not a shallow structure. In addition the location of SFR 3 in a rock block surrounded by major deformation zones might disturb the regional stress field presented by SKB. Even if existing underground facility in SFR 1 did not show notable instability problem, SFR 3 need more careful design approach since it is located around 60 m deeper than SFR 1 which will exert higher stress and it is surrounded by major deformation zones that might modify the regional stress field at Forsmark.

The rock mass in the Forsmark area is characterized by extensive sheet joints from the rebound of the removal of loading from overburden sedimentary rock and ice sheets. The sheet joints are sub-horizontal open or closed joints and have a large extension. The joints are water conducting and form a hydrogeological domain with anisotropic permeability. Close to the ground surface the joints are filled with glacial sediments. The results of the site investigation for the extension of SFR have shown that there is a risk that sheet joints can reach the depth of the roof of some of the vaults. Therefore, the influence of probable sheet joints intersecting the vaults and their effect on the roof stability of the vaults should have been simulated in the 3-DEC modeling study. The modeling result should provide information about the proper geometry of the vaults with respect to the existing excess of horizontal rock stress in the SFR area. SKB claims that the result of the 3-DEC analysis has shown that the pillars are stable. The influence of sheet joints and pillar size on pillar stability is warranty.

We believe comprehensive long-term and large-scale mechanical stability analysis of SFR extension is critically important for the safety and this has to be appropriately considered according to the license application schedule.

3.9.3. Integration with site description report

Although there was a separate study focusing on the rock mechanics parameters in site description study (SKB TR-11-04), the results of the site description was not properly considered in this analysis. An example is the different rock stress models in the two studies. Apparently the old data from 2002 was used for the long-term stability analysis. This incompatibility should have been avoided.

Table 1: Rock stress model used in the analysis.

	SKB (2013)	Mas Ivars et al. (2014)
Major horizontal stress (orientation)	5 + 0.07z (142°)	4.8 + 0.095z (120°)
Minor horizontal stress	0.07z	1.4 + 0.028z

3.9.4. Monitoring and calibration of rock displacements

It appears that no effort has been made to calibrate the values of the displacements predicted by the numerical model against any in-situ measurement from the construction and operation of SFR 1.

As there are a lot of monitoring data, SKB should be in a good position to be able to use monitoring data and calibrate the numerical model. This will then validate the numerical results.

The maximum displacement at the end of the excavation was evaluated to be between 2.5 and 5.5 cm depending on the tunnel section applied. This could be compared with available actual measurements, and furthermore, a criterion to judge whether this is acceptable or not should be set up by SKB. Any relation with the requirements in the EUROCODE should also be mentioned.

3.9.5. Consideration of groundwater

This analysis is conducted in a purely mechanical manner. It was stated in the report that the existence of water pore pressure can deteriorate the frictional properties of fractures and reduce the effective normal stress, which make the fracture more vulnerable to sliding.

SKB states that coupled hydro-mechanical analyses are time consuming but this cannot be used as a reason for not conducting an analysis given the importance of the safety assessment. More modelling or observational evidence considering the pore pressure at the SFR is needed since this can be also potentially linked with the inflow observation and interpretation.

3.9.6. Other minor comments

In page 7, time span of 10,000 years is mentioned. It is not clear though if this analysis intend to model 10,000 years. The fracture strength degradation is not directly linked to time, e.g., in Figure 3-2. Because SKB TR-14-11 specifically mentioned that this analysis was run 10,000 years, this has to be clarified although it is acknowledged that engineering judgement is inevitable in this process.

3.9.7. Summary

- This report is not sufficient to evaluate the mechanical stability of all rock chambers in both SFR 1 and SFR 3 because this report focus only on two rock vaults (1 BMA and 1 BLA). This issue has to be investigated by SKB according to the licence application procedure and prior to submission of construction application

- Waste vaults in SFR 3 are directed toward North-East, which is almost perpendicular to the direction of major horizontal stress. There must be compelling argument for this decision, and stability analysis is needed for SFR 3 since it is located 60 m deeper than SFR 1 resulting in higher stresses.

- This study is conducted without considering the pore pressure and its change and coupled hydro-mechanical analysis can provide a more reliable insight into the long term mechanical and hydraulic behaviours.

- Calibration of rock displacement prediction in numerical modelling against measured in situ data would greatly improve the reliability of this numerical modelling.

- The input parameters used in this study was not chosen based on the data presented in the site description report (SKB, 2013).

3.10. F-PSAR- General description Part 1, Chapter 5, Description and function of SFR

This document refers to SKB Document 1245480 which is in Swedish "F-PSAR SFR - Allmän del 1 kapitel 5 - Anläggnings - ochfunktions-beskrivning".

3.10.1. Introduction

This report gives a description of the existing and planned underground facilities of SFR and their main construction, waste content and function (Figure 20). The structure of the report is such that first the existing facilities and their content and function are described followed by a similar description of the planned extension of SFR 3. This style of presentation makes it easy for the reader to follow and judge the description of present facilities and the improvements and modified construction of the planned facilities.

Buildings, system and components of special importance for the safety of SFR are presented in Section 5.2 of the report followed by a description of the individual buildings on the ground surface and the underground vaults and tunnels in Section 5.3. In Section 5.4, SKB describes the handling of the different waste materials and the different functions and operations when transporting and handling the waste materials underground. Criteria and principles for start of drift of the extended SFR and the establishment of technical security for start of the operation (the so-called STF documents) are presented in Section 5.5. The closure plan for SFR including all the underground vaults, tunnels and boreholes complete the content of the report, Section 5.6.

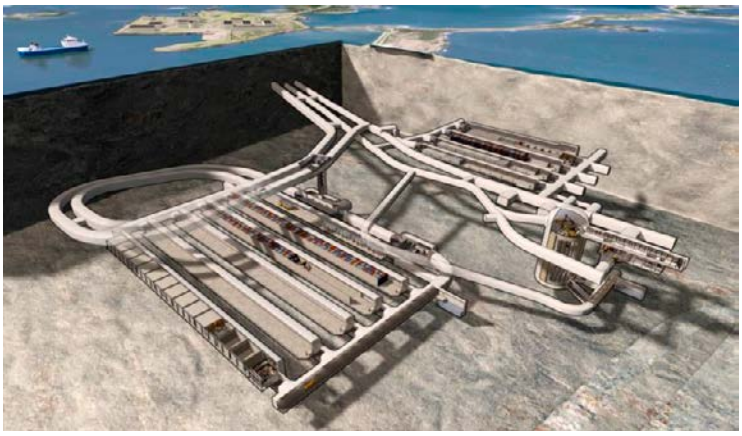


Figure 20: Overview of SFR 1 and SFR 3 (SKB Document ID 1245480).

3.10.2. Buildings, systems and components of importance for the security of SFR

The rock mass around all vaults in the underground facilities acts as a barrier after the closure of the facilities. The concrete structures including the casting around the waste in 1BMA and BMA, 1BTF and 2BTF and the Silo and the concrete around and inside the reactor tanks in 1BRT are the technical barriers after closure of SFR.

SKB are short describing the different facilities and buildings with special importance for the operational safety and long-term safety and radiation protection. The list contains the following items:

- Protection against fire
- Secure handling and deposit
- Physical protection
- Radiation protection

It is not clear from the text if SKB has given the individual items a ranking of importance for the operational and long-term safety. The text to each of the items is short and the reference to the internal numbering of each individual system makes it difficult to get the complete content of a specific item or system.

3.10.3. Description of the present and extended tunnels and vaults

SKB presents maps and descriptions of the buildings on the ground and of the new access tunnel to the expanded area of SFR and the six new vaults. The existing entrance to the underground facilities cannot be used for the new tunnel entrance designed for the transport of the long reactor vessels down to the vault, 1BRT. The new tunnel starts west of the existing entrance. The new tunnel is designed to intersect above the two existing tunnels and thereafter run parallel with the existing ones. The new tunnel will intersect the water bearing Singö deformation zone. Nowhere in the documents reviewed is written how the tunnel construction will be made through the zone and what permeability and inflow from the zone SKB intend to achieve. The plan of new tunnel construction through the Singö deformation zone calls for a special report and description of the hydro-mechanical conditions, estimated long-term stability and water inflow. At present the water leakage from the existing tunnels are flowing in open ditches to the pump pits at the bottom of the facility close to the Silo. The water flow creates high humidity of the circulating air which enhance the concrete degradation and corrosion. Directing the water inflow into pipes in the old and new tunnels will certainly reduce the humidity and improve the air conditions in the facility.

The tunnel ramp for transportation of waste to the extended repository is located parallel with the existing tunnels for a rather long distance and thereafter turn towards the South to reach the planned vaults. The tunnel makes a wide circle to reach the western parts of the vaults for reactor tanks, 1BRT. The operational tunnel reaching the technical installations, TIT is designed to deviate from the present operation tunnel to be located next to the transport tunnel. This lay-out of the tunnels means that the transport of the rather long reactor tanks will be directed to the tunnel with the smallest radius of curved tunnel sections. One would expect to find the opposite.

From the presented 3-D pictures (Fig.5-5) it is not clear if the radiological control building has an access to the lower construction tunnel (Nedre byggtunnel) and from there have an access to the drift building and radiological control building in the present SFR. This also raises the question why there needs to be two drift and control buildings for the extended SFR? In Section 5.4.8 about Common functions with other activities at Forsmark, SKB is stating that when the extended SFR is built. It seems most likely that a common operation and maintenance function is established for the two SFR deposits.

In 2BMA is planned to have 14 free standing caissons (Figure 21). In the safety analysis for 2BMA is stated that the caissons will be of unreinforced concrete and the walls and roof will be lined with shotcrete. The design is different from 1BMA and raises the question why the caissons are made unreinforced and what is the purpose of using shotcrete on their walls and roof? Further, SKB has not presented what type of construction will be made to prevent drops from the roof into the caissons.

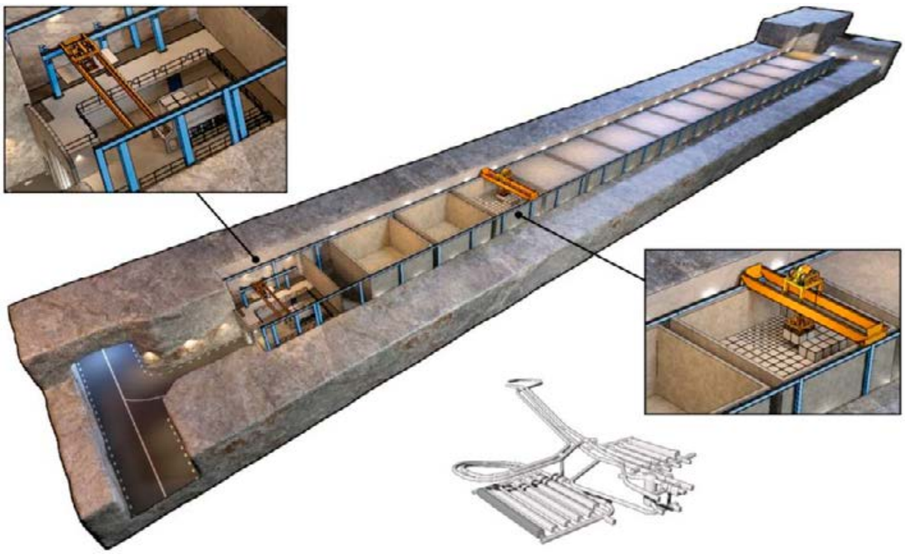


Figure 21: Overview of 2BMA (SKB Document ID 1245480).

The 2-5BLA vaults for low-level waste will have a slightly different construction compared to 1BLA. The stacked ISO containers will be supported with reinforced concrete walls to ensure stability of the containers. On top of the containers and on the concrete walls shotcrete will be applied. It is not clear how the concrete will be applied to the top of the containers to reach an acceptable strength of the structure.

3.10.4. Drainage and ventilation

All leakage water in SFR is flowing into four low points, two into existing SFR and two into the extended parts and illustrated in Fig. 5-18. At the low points in the underground facility the water is collected in basins and pumped to the surface and further into the sea. It is of utmost importance that the amount of flowing leakage water in open ditches of the tunnels and vaults is reduced to limit the amount concrete degradation and steel corrosion (see section 5.3).

The ventilation in the underground facilities is divided into two separate systems, one for the operation of SFR and one for the construction work. The climate in the underground facilities is very sensitive to the weather conditions during the summer and winter season. The ventilation system for the operational parts of the facility has the following tasks:

- Ventilation of underground facilities so that existing hygienic limits are kept
- Prevent air carried activity from malfunctions from any vault
- Evacuation smoke from fire

In addition, the existing and future ventilation system in the extended facility needs to be improved or changed to improve or stop the ongoing degradation of concrete and steel in the existing SFR and prevent degradation of the extended facilities. Also the limit values of allowed leakage to the extended tunnels and vaults need to be specified with the aim to reduce the leakage.

3.10.5. Summary

- The planning of a new tunnel construction through the Singö deformation zone calls for a special report and description of the hydro-mechanical conditions, construction method, and estimated long-term stability and water inflow.

- Which are the main reasons for constructing an additional operation and control building for the extended SFR facility? SKB is planning to organise a common operation and maintenance function for the two SFR deposits.

- The design of 2BMA is different from 1BMA and raises the question why the caissons are made unreinforced concrete and what is the purpose of using shotcrete on the walls and roof of the vault?

3.11. F-PSAR SFR - General Part 1,Chapter 5 - SFR Closure Plan

This document refers to SKB Document ID 1358612 in Swedish “Allmän del 1 kapitel 5, SFR förslutningsplan”.

3.11.1. Introduction

After decision of final closure of SFR is taken, the decommissioning of some of the underground buildings and structures begins. At the same time, activities are carried out until the extended SFR repository has been completely sealed. After sealing and closure of SFR, the underground facilities are left and will function as an inactive repository and no further action or control are needed and wanted.

In this report about SFR closure plan, SKB describes the possible design options and methods for installation of the sealing components for the individual vaults in the present SFR facility and its proposed extension. SKB is designed to receive the short-lived radioactive waste from the Swedish reactors and waste from the decommissioning of the shutdown reactors. For each of the vaults SKB describes the design basis for grouting the waste packages. As the waste will be different in the vaults the method of grouting and the composition of the grout will differ in the vaults.

When the repository is filled with waste and the grouting of the waste packages is completed, sealing and closure will begin. The closure means that concrete plugs and different backfills are installed with the aim to reduce water flow around the waste packages and hinder human access to the underground facilities. The Silo and vaults will be backfilled with macadam. The access tunnels and connecting tunnels between the vaults and other parts of the facility will be backfilled with macadam.

The aim of the closure plan is to present a comprehensive description of design and installations of the underground facilities based on determining construction assumptions. In addition the closure plan will give an integrated description of the function of the different barriers and the grouting at closure. The long-term safety is one of the most important factors in designing the barriers and their ability to prevent and delay the release of radioactive material.

3.11.2. Grouting of waste

The aim of the grouting is to protect the waste against fire and radiation, stabilise the tilting of the waste packages and generate a suitable construction for the final closure of the repository. In addition the grouting has the purpose of preventing leaking water to reach a direct contact with the waste material.

In the vaults 1BMA, 2BMA, 1BTF and 2BTF and the Silo grouting will be conducted during operation of the underground facility. The specification of radiation protections and the type and thickness of grout are specified in Section 3.1.2 of the report.

1BMA

The present status of the concrete structures in 1BMA is described in Section 3.2 of the report. Major repairing works and reinforcement are needed of the concrete structure in the vault in order to maintain the operation and to achieve the initial condition prior to closure of 1BMA. The delaminating of the concrete and the following corrosion of the steel reinforcement have caused reduction of the loading capacity of vault and reduced radiation protection during recent operation. Through going fractures in the concrete structure has to be sealed and new concrete casted.

There is a need of developing a new type of injection grout for 1BMA that gives a better end-product after hardening. To prevent too high fluid pressure during casting the grout, the filling heights during grouting has to be reduced during operation.

The present situation with concrete damage and corrosion in 1BMA and the need of developing a new grouting concept are important tasks for the daily operation and for maintaining both the short-term and long-term safety of SFR.

The Silo

The Silo is a vertical cylindrical storage of reinforced concrete located in the rock mass. A thick layer of compacted sand-bentonite mixture is placed between the concrete cylinder and the rock mass. The waste is placed in 57 large shafts and more than a dozen small shafts. During operation of SFR the waste is deposited in the shafts and grouted with a special cement-based grout with a load carrying capacity to prevent the waste containers to collapse from the load above. After the discovery in 2010 of water leakage in some of the shafts of the Silo the operation was stopped and SKB has initiated and conducted a series of special investigations about the leakage and the consequences for the quality of the performed waste storage. After resolving the cause and effects of the leakage, the development of a new type of grout and improved grout emplacement technique, SKB should be ready to continue loading of intermediate waste in the shafts of the Silo.

1BTF

The vault of 1BTF is used for storage of concrete tanks of waste and steel barrels with ash from burning low-active waste. The concrete tanks are placed along the wall of the vault to prevent the barrels to roll against the rock wall. Additional concrete tanks and steel plates are installed between the long walls of the vault. Plastic sheets and steel plates are added before casting the lid if the waste section. The steel barrels are casted from boreholes drilled through the pre-fabricated concrete elements. Grouting of the barrels takes place during operation and grouting of the concrete tanks at the time of closure.

Grouting of the space between the concrete tanks and the rock wall will be done at the time of closing the repository. The suggested method to insert 50 mm thick rock wool sheets between the rock wall and the concrete tanks seems complicated and difficult to control. The emplacement of the rock wool sheets to the entire height of almost 5 m seems to be a difficult task and difficult to quality control.

A concrete plate will be casted on top of the pre-fabricated lid. The plate and the lid have to carry the weight of the backfill of macadam to the roof of the vault. The total weight of the backfill concrete plate and lid has to be carried by the concrete tanks. The load bearing capacity of the tanks is not mentioned in the description of closure of 1BTF.

2BTF

The vault of 2BTF is used for storage of concrete tanks with waste. The tanks are placed four in width and two on top of each other. Pre-fabricated concrete elements are placed on top of the concrete tanks and later casted with grout at the time of closure of the repository. The anticipated problems with installation of rock wool sheets etc. are the same as for closure of 1BTF.

2BMA

In the vault of 2BMA, free standing concrete structures without steel reinforcement are planned to be constructed. In every section of 2BMA, the waste will be emplaced by means of a traverse moving on a separate concrete structure. Based on the experience from 1BMA the distance between waste packages will be increased to 100 mm to guarantee a satisfactory grouting. This increase of the spacing means more concrete is added to the wall of the interior structure, which is positive for the loading capacity and stability of the non-reinforced structure.

During grouting at the closure of the vault, the walls of the concrete structure need support. SKB is suggesting to apply wires or concrete supports against the rock walls in the vault. To avoid a collapse of any of the structures in the vault, concrete support against the rock walls of the vault is recommended otherwise the maximum height of the grouting has to be reduced from the suggested 3.1 m. In addition, the cement grout needs to be developed by SKB to suite the casting of the waste in 2BMA.

1BRT

In the vault 1BRT, SKB plan to deposit reactor tanks from decommissioned nuclear power stations. A total of nine reactor tanks will be placed in a row of the vault. The reactor tanks have a length that varies between 18 and 22 m and a diameter between 5.8 and 7.2 m. The primary function of the grouting is to minimize leakage of radioactive substances by reducing the corrosion of the reactor tanks. The casting with cement grout increases the pH, reduces the rate of corrosion and increases the sorption capacity. SKB is studying methods of casting with concrete or cement-based grout and their applicability with respect to radiation and geometry of the space around the tanks. These studies to be performed by SKB are found to be relevant for the long-term safety of the disposal of reactor tanks.

3.11.3. Closure of SFR

The construction conditions for closure of SFR are based on the assumptions made in previous safety analyses SAR-08 from year 2008 (SKB R-08-130). In Section 4.1.1 of the closure report SKB presents the type of closure of the different vaults, the Silo, access tunnels and other tunnels in the existing and extended SFR. Based on the estimated inflow to the tunnel system at the location of plugs in existing and planned extension of SFR, SKB has estimated the leakage for the different tunnels. The calculation or modelling methods applied for obtaining the estimated inflow are not presented in the report.

In section 4.2.2 and Figure 4-2 of the report SKB is presenting a possible sequence for the closure of SFR (Figure 22). The order in which the individual vaults, the Silo and tunnels are filled, plugged and left is logical and well thought through. However, there exist tunnel sections in SFR where the water inflow is high, e.g. the lower tunnel to the Silo, where grouting is needed before placing the backfill. To solve some of these problems SKB is referring to ongoing development work within the project for final disposal of spent nuclear fuel.

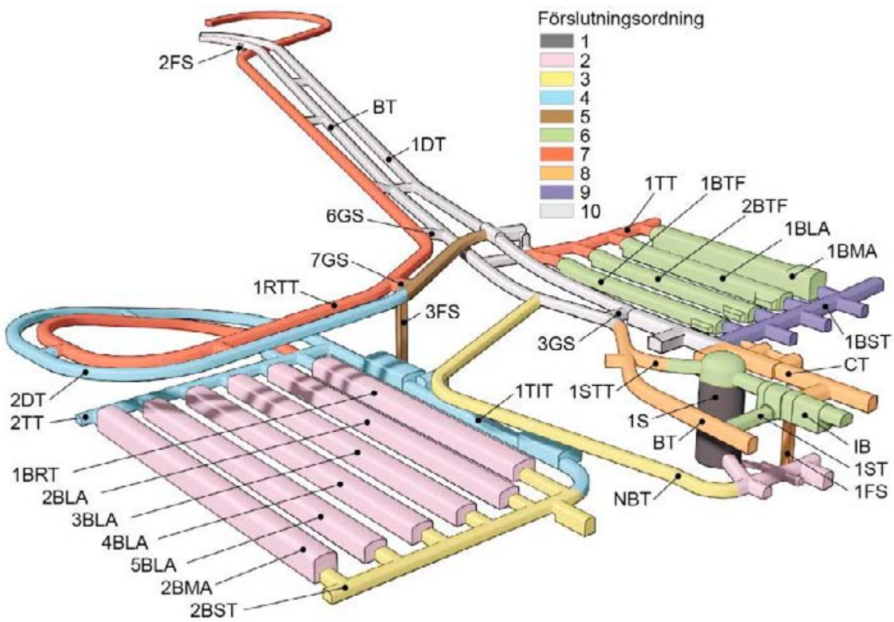


Figure 22: Sequence of closing plan for SFR. The colours represent the order of closing and not the borders of different filling materials (SKB Document ID 1358612).

In section 4.3.2 SKB presents the motives for the design of backfilling material for the vaults in SFR (Figure 23). For some of the vaults SKB intend to install rock wool sheets at the contact between the rock wall and the concrete barriers. If SKB wants to construct a "hydraulic cage" around the concrete barriers in the vaults it might be better to construct the high permeable structure prior to the construction of the concrete barriers in the vaults. SKB should also consider to leave the EDZ in the tunnel walls and use the EDZ as a part of the cage instead of removing the EDZ and later install rock wool sheets.

3.11.4. Continuous technical development and verification

In Chapter 6 of the Plan for closure of SFR, grouting around the different waste forms in the vaults and sealing of the vaults are identified as areas for further technical development and verification. In particular SKB needs to develop new application technique for grouting around the different waste forms in particular for 1BMA, 1BTF and2BTF. Also, there is a strong need to develop new and better cement-based grout material to achieve better stability during grouting, better sorption properties and higher compressive strength properties. Also SKB has to decide about the quality of the concrete to be used for the concrete structures underground in order to avoid degradation and corrosion.

SKB has listed eight different areas in the field of closure of SFR that need additional technical development and verification of the end product. All the listed areas for further research and development are relevant and needed.

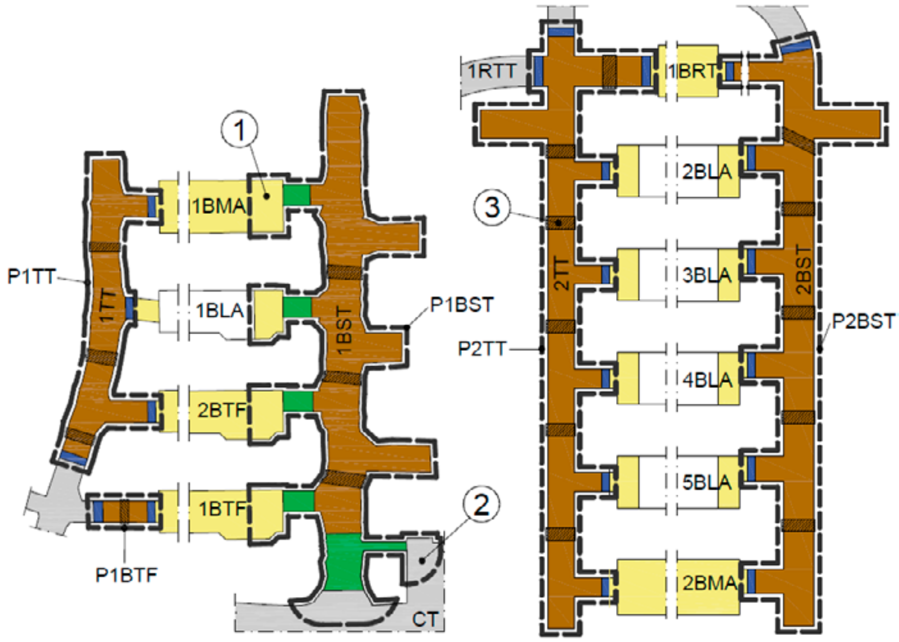


Figure 23: Plugs for the waste vaults at their entrance. The white line at the rock contour illustrates the removal of the damage zone (EDZ) prior to backfilling of the tunnels (SKB Document 1358612).

3.11.5. Summary

- The present situation with concrete damage and corrosion in 1BMA and the need of developing a new grouting concept are important tasks for the daily operation and for maintaining both the short-term and long-term safety of SFR.

- After resolving the cause and effects of the leakage of water in the Silo, development of a new type of grout and improved grout emplacement technique, SKB should be ready to continue disposing of intermediate waste in the shafts of the Silo.

- The suggested method to insert 50 mm thick rock wool sheets between the rock wall and the concrete tanks in 1BTF and 2BTF seems complicated and difficult to control. The emplacement of the rock wool sheets to the entire barrier height of almost 5 m seems to be a difficult task and difficult to quality control.

- To avoid a collapse of any of the barrier structures in 2BMA, concrete support against the rock walls of the vault is recommended or the maximum height of the grouting has to be reduced from the suggested 3.1 m.

- In Chapter 6 of the Plan for closure of SFR, grouting around the different waste forms in the vaults and sealing of the vaults are identified as areas for further technical development and verification.

4. Suggested topics for the Main Review Phase

Based on the overall assessment of SKB's application for SFR extension, the following topics are suggested for detailed review at SSM's Main Review Phase. The general topics listed below suggest an order of priority for the review.

- Long-term stability of SFR chambers and the impact of climate changes and future glaciations
- Effect of earthquakes on nearby faults and the stability of SFR caverns
- Systematic methodology for rock mass property determination
- The effect of rock support degradation on the long-term performance of SFR
- Suitability of the location of the SFR extension.

4.1. Long-term stability of SFR chambers and the impact of climate changes and future glaciations

SFR is designed as a subsea hard-rock facility which is reached via access tunnels from a surface facility. SFR 1, which comprises of a Silo and four waste vaults located about 60 m beneath the surface of the sea with the bottom of the Silo located about 70 m beneath. SFR 3 is planned to have six waste repository vaults that will be located at about 130 m beneath the surface of the sea as shown in Figure 24 (SKB TR-14-01).

Ensuring the mechanical stability of existing SFR 1 and new facility SFR 3 is of prime importance for the safety assessment. Especially most of stability analysis for Silo in SFR 1 is outdated without due consideration of new monitoring data, and no predictive modelling has been made for the mechanical stability of SFR 3. Numerical modelling for predictive analyses can provide valuable insight into the long-term behaviour of underground cavern. Systematic case studies are available in Canada and USA (Kemeny, 2005; Damjanac et al., 2007; Itasca, 2011). Because the rock chambers in SFR 3 are planned to be directed toward North-East direction which is almost perpendicular to the direction of major horizontal stress, its effect needs to be evaluated as well. In addition the influence of the major deformation zones surrounding SFR 3 and the possibility that sheet joints might reach the depth of the roof of the vaults are additional problems to be analysed.

The mechanical conditions of the bedrock around SFR are not expected to change significantly during the assessment period up to 100,000 years. SKB states that the rock stresses will only change to a small extent, but not in such a way that the conditions for the repository stability and long-term safety are altered. However, the glacial rebound and the Forsmark area is about 6 mm per annum. In 10,000 years the repository area will rise 60 m from the present ground surface of SFR. The facility will be located above the sea level with groundwater table. During this process, the flow path of the groundwater and the effective stress in the rock mass will change.

Glacial Isostatic Rebound (GIA) is expected to be around 6 mm/year within the assessment period. It is expected to take 1,200 to 2,200 years for the seabed on top of the rock cavern to be exposed to surface. The effect of this uplift has never been investigated by SKB in the context of coupled hydro-mechanical processes occurring near the underground chambers. The long-term change will have impact on groundwater pressure distribution and in-situ stress conditions. These changes might then have impact on the mechanical stability and trigger earthquakes along critical loaded faults. Quantitative simulations of the present monitored inflow into the facility and predictions for the future can be provided.

The detailed issues to be explored for the long-term stability of SFR 1 and SFR 3 are:

- Systematic long-term mechanical stability of SFR considering degradation and orientation of in-situ stress,
- Change of in-situ stress and groundwater field due to shoreline displacement,
- Coupled hydro-mechanical analysis to model the inflow into the tunnel,
- Potential triggering mechanism of earthquake from glacial rebound.

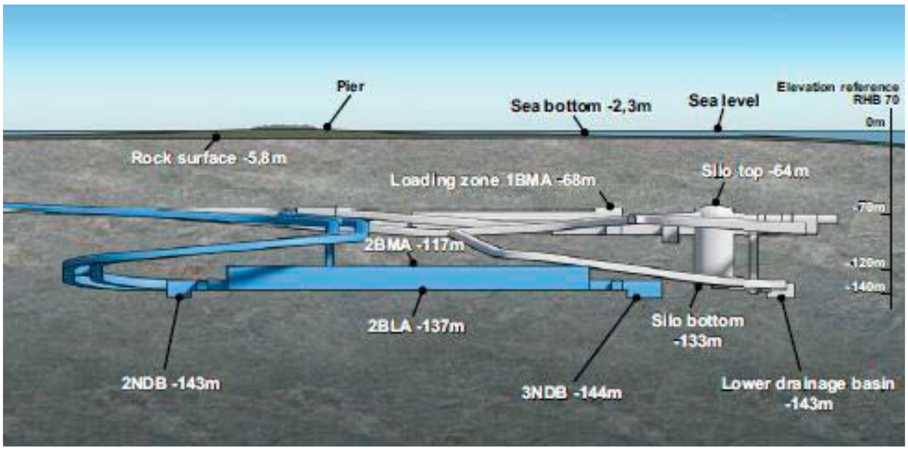


Figure 24: View of SFR1 (grey) and SFR 3 (blue) with designated levels. View is towards the NW, approximately perpendicular to the waste vaults (Main report, SKB TR-14-01).

4.2. Effect of earthquakes on nearby faults and the stability of the SFR vaults

Although earthquakes and related hazards in Scandinavia are today not of major concern, due attention has to be given to the issue due to extremely long time-span on which the safety performance of the repository is expected.

SKB's earthquake modelling was focused on concrete structures and the conclusion was that earthquakes with annual frequency of 10^{-6} and 10^{-7} can threaten the safety of the concrete structures in the Silo. No analysis was conducted for underground rock vaults where the Silo is located. Furthermore, the stability of rock caverns close to a large scale deformation zone (i.e. Singö zone) has been identified during the construction of SFR 1 (Figure 25). Therefore, it is necessary to conduct a safety assessment of the reinforced rock chamber against earthquakes located at any of the adjacent faults surrounding the area of SFR extension. Possible impact of the future

construction of geological repository for spent nuclear fuel, which will be located 1.5 km apart, has to be investigated systematically.
The detailed issues to be explored are;

- SFR vault stability due to earthquakes,
- Effect of nearby major faults on the stability of SFR,
- Effect of heat load from spent nuclear fuel repository on faults and vault stability in the area of SFR 3.

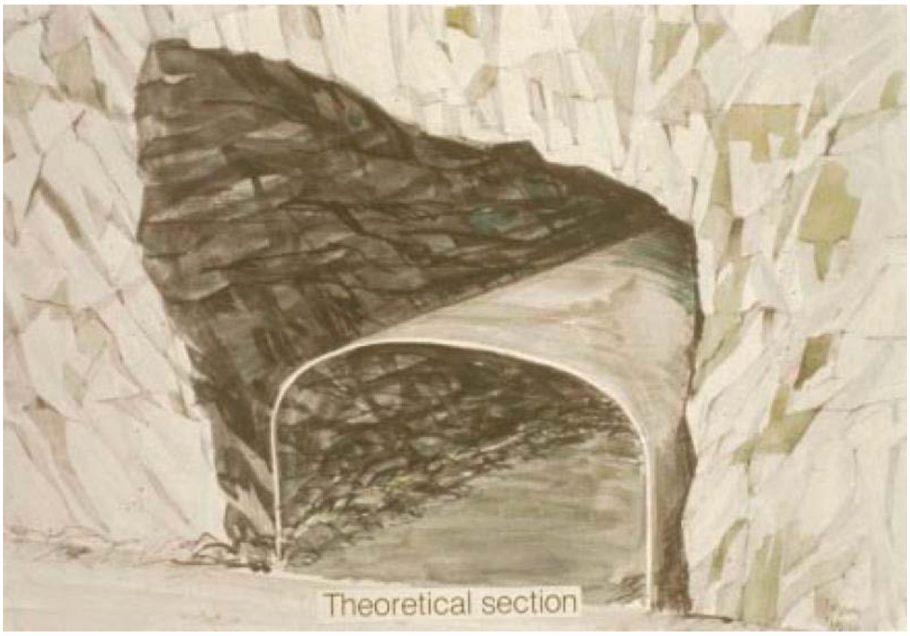


Figure 25: Maximum overbreak of 7.5 m above the theoretical roof of the access tunnel section at linkage 2/545 across the Singö deformation zone was observed during construction of SFR1 (Carlsson and Christiansson, 2007).

4.3. Systematic methodology for rock mass property determination

The properties of rock mass are different from those of intact rock, and there are numerous techniques to determine or estimate them. Although SKB seems to have recognized the importance of such distinction, no due attention was given to more elaborate testing and analysis to determine the rock mass properties such as elastic modulus, Poisson's ratio and strength parameters based on empirical relations or on the properties of the intact rock and rock fractures. SKB decided to use existing old data from the construction of SFR 1 and from the site investigations for the planned repository of spent nuclear fuel. Furthermore, there is no explanation how the rock mass properties were determined (i.e. table 6-8 in SKB, 2013). This is especially disappointing as SKB has developed extensive methodology of theoretical, empirical and numerical approaches to determine rock mass properties that can be applied to any rock engineering facility (Röshoff et al., 2002; Olofsson and Fredriksson, 2005). The key consideration in determining the rock mass properties is the highly non-linear fracture behaviour and this has to be properly considered for the design of a facility in a fractured rock mass. This kind of studies can be possibly linked to a strategy of confirmation of loads, deformation and inflow during SFR 3 construction through in-situ testing and monitoring.

Min et al. (2005) applied the so-called DFN-DEM approach to obtain rock mass properties at Forsmark area with the support of SSM's predecessor the Swedish Nuclear Power Inspectorate (SKI). The results show that the rock mass properties are stress dependent, hence, depend on depth and water pressure. The elastic modulus at the depth 100 m is around half of that at the depth of 400 m, which shows that the consideration of depth is important and empirical approach has limitation in properly addressing this issue (Figure 26).

The detailed issues to be explored regarding rock mass mechanical parameters during the Main Review Phase are:

- Determination of rock mass deformation properties in both 2D and 3D using DFN-DEM approach,
- Determination of rock mass strength properties in both 2D and 3D using DFN-DEM approach,
- Calibration and validation of strength and deformability results for rock masses against measurements, empirical observations and analytical solutions during construction and operation of SFR 1.

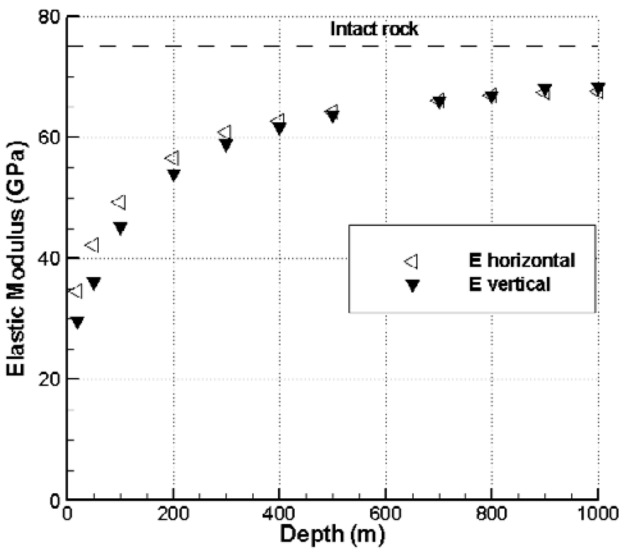


Figure 26: Stress (and depth) dependent elastic moduli of fractured rock mass from Forsmark (Min et al., 2005).

4.4. The effect of rock support degradation on the long-term performance of SFR

Shotcrete, rock bolts and concrete structures are important rock supports used in SFR 1 today and in the planned extension. At the time scale of thousands of years, degradation occurs and their performance has to be evaluated in a more quantitative manner as a function of time. This is also true during the operational period when rock support degradation can happen due to the corrosive groundwater and air quality inside SFR.

At present SKB is performing long-term testing of rock reinforcements in SFR 1. It is not mentioned in the reports whereas SKB will extend the ongoing test program or develop a new program specific for SFR 3.

An independent study sponsored by SSM on water leakage and degradation of rock support could be a starting point (Bogdanoff, 2013). Water is the main reason for degradation of rock support like shotcrete, rock bolts and nets is one of the main conclusions of the report. The authors is using the present information regarding previous decrease and present increase of water leakage into SFR 1 and CLAB to point at changing groundwater pressure as the main reason for changes of water leakage with time. New fracturing from blasting and drilling of the borehole for rock bolts is a common reason for degradation of rock bolts. Shotcrete is often used in underground constructions to support and dry the structure. This demands a dry rock surface when the shotcrete is applied, which is usually overlooked. The content and conclusions in the report by Bogdanoff, (op. cit) gives a good starting point in establishing.

The detailed issues to be explored in the Main Review Phase are:

- Literature review on the observation of rock support degradation including analogue study to predict the long term behaviour of rock support material,
- groundwater pressure dependency on leakage into vaults and tunnels
- Time dependent stability analysis of SFR with degrading rock supports,
- Upgrading of existing long-term rock support degradation testing program for SFR 1 and SFR 3.

4.5. Suitability of the location and layout of the SFR extension

SFR extension is currently located in the rock mass south of the existing SFR 1. The current location of the SFR extension was decided prior to the main site investigation. Geophysical investigations indicate good rock conditions exists for an extension in the East of SFR 1.

The waste vaults in SFR 3 are planned to be directed towards North-East which is almost perpendicular to the major horizontal stress, and this unusual design concept also needs to be evaluated. Possible impact of the planned underground repository for nuclear spent fuel also needs to be investigated in terms of thermal stress, stress disturbance and possible triggered earthquakes.

The detailed issues to be explored in the Main Review Phase are;

- Re-interpretation of the geophysical data and diamond core drilling data for the area East of SFR 1,
- Evaluation of location, structure, and depth of SFR 3 considering existing deformation zones and in situ stress,
- Site investigation for the development of a common underground operative centre for SFR 1 and SFR 3,

- Impact of the planned repository for nuclear spent fuel on SFR 1 and SFR 3.

5. The Consultants' general statement

The Swedish Radiation Safety Authority (SSM) has received an application for the extension of SKB's final repository for short-lived low and intermediate level waste at Forsmark (SFR). The Consultants' general statement on SKB's applications documents with regards to rock engineering and engineering geology is summarized here.

SKB is complimented on the comprehensive and integrated safety analysis. The investigations provided to support the licence application are made by SKB staff and consultants. These are of international class and technical reports are written and organized in a professional way. Given the many uncertainties associated with the design and construction of an underground repository, the width of the database, the performance of the safety assessment and the quality of reporting are judged to be of high standard. SKB is in a unique position in the world to possess the experience of operation of the underground repository SFR 1 for almost thirty years.

The strongest merit of SKB's application documents is that SKB already has proven records of operating SFR 1 with continuous monitoring. This experience has helped the thorough investigation necessary for the extension of the existing repository. Furthermore, extensive site investigations conducted at Forsmark for the planned deep repository of spent nuclear fuel has allowed for improvement in the general understanding of the area and in particular the area west of SFR.

On the other hand, it needs to be mentioned that SFR is only in the initial period of its technical life time, and a lot of uncertainties still remain to be resolved, which require substantial amount of work to be conducted. This should be done through comprehensive design, engagement during construction, elaborate monitoring strategy and continued R&D programme. An extensive programme for the future SFR 3 will in turn also help the construction and operation of deep repository for nuclear spent fuel.

There are a number of limitations and weakness noticed through the Initial Review Phase as follows;

- Determination of rock mass properties for SFR extension,
- Long-term and large-scale stability analyses,
- Effect of groundwater on stability of rock vaults,
- Effect of shoreline evolution and other climatic changes on rock vault stability,
- Improved analysis on the effect of earthquakes,
- General evaluation of the location and layout of SFR 3.

The issues above are elaborated in Chapter 2 and 4 of this report. Overall, SKB is recommended to perform more in-depth technical analyses and adopt newer technologies for solving the rock mechanics and rock engineering problems at SFR. Although the regulations regarding low and intermediate level nuclear waste may be less strict than for spent nuclear fuel, additional investigations are still necessary to comply with the regulatory requirements set by SSM according to the license application schedule.

The general structure, transparency and traceability of SKB's application documents are acceptable. Essential information is collected, integrated and well-presented into the Main Report with relevant citation to the Main References. Technical descriptions provided in the Main Report can be traced back to the Main References and Additional References. Most of the documents are accessible to the general public and their presentations are judged to be transparent.

Nonetheless, it needs to be pointed out that more thorough and traceable verification of the used numerical codes and models for this application is necessary. As emphasized in Section 3.6.3 in the current report, verification cases need to be presented even when the code is widely used by professionals since verification also include the qualification of modelers using the codes. Some of the mechanical parameters such as in-situ stress presented in the reports are not compatible with each other and this shows that the process of safety assessment has room for improvement (see Section 3.9.3). Currently, the location of planned deep repository for nuclear spent fuel seems to be omitted in most of the figures in the SKB application report, and this needs to be corrected to improve the transparency.

The general scientific quality of SKB's application documents is considered to be of high standard and modern state-of-the-art technology is being employed. However, more efforts need to be made in order to make use of best available techniques or even to develop new technology functional to the safety of the underground facility. The most up-to-date site descriptive model version seems to be 1.0, but some data from older versions is also used. The data need to be more fully integrated. Currently, the technology to monitor fracture displacement in both shear and normal direction is available (see section 2.2.2) and more elaborate long-term stability analysis has been conducted in the US and Canada (see section 4.1).

Based on the findings from the Initial Review Phase, topics which require additional review for the Main Review phase areas follows in the order or priority:

- Long-term stability of SFR chambers and the impact of climate changes and future glaciations,
- Effect of earthquakes on nearby faults and the stability of SFR caverns,
- Systematic methodology for rock mass property determination,
- The effect of rock support degradation on the long-term performance of SFR,
- Suitability of the location and layout of the SFR extension.

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SKB (2014). Data report for the safety assessment SR-PSU, SKB TR-14-10, Swedish Nuclear Fuel and Waste Management Co (SKB).

SKB (2014). Model summary report for the safety assessment SR-PSU, SKB TR-14-11, Swedish Nuclear Fuel and Waste Management Co (SKB).

SKB (2014). Input data report for the safety assessment, SKB TR-14-12, Swedish Nuclear Fuel and Waste Management Co (SKB).

SKB (2014). Allmän del 1 kapitel 5, Anläggnings- och funktionsbeskrivning, SKB DokumentID 1245480 (in Swedish),Swedish Nuclear Fuel and Waste Management Co (SKB).

SKB (2014). Allmän del 1 kapitel 5, SFR förslutningsplan, SKB DokumentID 1358612 (in Swedish),Swedish Nuclear Fuel and Waste Management Co (SKB).

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SSM (2008). The Swedish Radiation Safety Authority's regulations concerning safety in connection with the disposal of nuclear material and nuclear waste, SSMFS 2008:21, Swedish Radiation Safety Authority (SSM).

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Stille H and Fredriksson A (1988).Measurements, Calculations and Stability Prognoses at the SFR Undersea Repository for Low- and Medium-Level Nuclear Waste, *Tunnel Undergr Space Tech* 3(3):277-282.

Coverage of SKB reports

The following reports have been covered in the Initial Review Phase.

Table 1: Coverage of SKB reports

Reviewed report	Reviewed sections	Comments
[SKB TR-14-01, Safety Analysis for SFR, Long-term safety, Main report for the safety assessment SR-PSU]	*[Section 4.3, 4.4, 4.6, 4.7, 5, 6, 7.4, 7.5, 7.6, 7.7, 7.8, 7.9, 8 and Chapter 11]*	*[section 3.1 of this report]*
[SKB TR-11-04, Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark]	*[Section 2, 3, 4, 5, 6, 7, 9, 10]*	*[section 3.2 of this report]*
[SKB TR-14-10, Data report for the safety assessment SR-PSU]	*[Chapter 2, 8, 11,12]*	*[section 3.3 of this report]*
[SKB TR-14-07, FEP report for the safety assessment SR-PSU]	*Relevant sections*	*[section 3.4 of this report]*
[SKB TR-14-02, Initial state report for the safety assessment SR-PSU]	*[Chapter 4, 5, 6, 7, 8, 9, 10,11,12]*	*[section 3.5 of this report]*
[SKB TR-14-11, Model summary report for the safety assessment SR-PSU]	*[Chapter 2 and Section 3.1]*	*[section 3.6 of this report]*
[SKB TR-14-12, Input data report for the safety assessment]	*Relevant sections*	*[section 3.7 of this report]*
[SKB R-13-52, A seismic evaluation of SFR. Analysis of the Silo structure for earthquake load]	*Whole report*	*[section 3.8 of this report]*
[SKB R-13-53, Long term stability of rock caverns BMA and BLA of SFR, Forsmark]	*Whole report*	*[section 3.9 of this report]*
[Allmän del 1 kapitel 5, Anläggnings- och funktionsbeskrivning, SKB DokumentID 1245480 (in Swedish)]	*Whole report*	*[section 3.10 of this report]*
[Allmän del 1 kapitel 5, SFR förslutningsplan, SKB DokumentID 1358612 (in Swedish)]	*Whole report*	*[section 3.11 of this report]*

APPENDIX 2

Suggested needs for complementary information from SKB

1. [SKB TR-11-04, section 6.5.1 and 6.5.2] The whole paragraph is repeated in two section and this must be corrected.
2. [SKB TR-14-10, Table 11-2] In the report there is a lack of information about the content and modelling conditions of the presented data files in a table. This information needs to be provided in order to judge the results of the presented data files.
3. [SKB TR-14-07 FEP K9.06]The only way to know if heating of the repository for spent fuel can cause stress changes at the SFR site and its vicinity that can lead to hydrogeological effects through 3-D T-H-M modelling. New FEP is needed.
4. [SKB TR-14-02, page 97]It was stated that some boreholes sealed after investigation for SFR 1 may not fulfil the current requirements. Fuller explanation needs to be given on this remark.
5. [SKB TR-14-11 Code manuals] In order to confirm that the code is verified SKB should either provide verification cases which can be taken from manual, or provide the manual to SSM.
6. [SKB R-13-52, page14] The effect of ground water and groundwater pressure was not considered in this earthquake analysis, and the reason was not clearly explained by SKB.
7. [SKB R-13-53, Eq.3.3 in page 18] It is a wrong equation because it simply returns zero.
8. [SKB R-13-53, Table 2-9] In situ stress used in this table in different from the one used in TR-11-04 (table 6-11). This needs further explanation.
9. [SKB R-13-53, Table 2-1] DFN statistics shown in Table 2-1 is not complete and there must be more information regarding fracture density and fracture length.
10. [SKB R-13-53, page 7] 10,000 years was mentioned, but it is not clear whether the numerical modelling in this study is intended to cover this period. A clearer explanation regarding the modelling period and strength properties reduction has to be provided.
11. [SKB Document ID 1245480; Description and function of SFR] The new transport tunnel will intersect the Singö deformation zone. A plan for tunneling through the zone is missing.
12. [SKB Document ID 1245480; Description and function of SFR] In the safety analysis for 2BMA, it is stated that the caissons will be of unreinforced concrete and the walls and roof will be lined with shotcrete. The reasons for this decision has to be more clearly presented.
13. [SKB Document ID 1358612; Closing the SFR repository, Section 4.1.1] Remarks on the present status of the grout and concrete structures is needed

given the uncertainties associated with their sorption properties, strength and degradation.

APPENDIX 3

Suggested review topics for SSM

1. Long term stability of SFR chambers and impact of climate change and future glaciation
2. Effect of earthquakes on nearby faults and the stability of SFR caverns
3. Systematic methodology for rock mass property determination
4. The effect of rock support degradation on the performance of SFR
5. Suitability of the location and layout of the SFR extension.

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4

Review of the inventory of chemical substances in the waste and waste packaging

Activity number: 3030014-1011
Registration number: SSM2015-2551
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Abstract

This document provides a review of the inventory of chemical substances in the waste and waste packaging of SFR as presented in the SR-PSU. The review considers how SKB have identified chemical substances that could affect long-term safety. The review examines how the uncertainties in the amounts and effects of these substances on radionuclide transport have been assessed. An assessment of the clarity and completeness of SKB's documentation has been made.

The main conclusion of the review is that SKB have identified the main chemical substances (cellulose and disposed organic complexants) that could affect radionuclide transport. The method of assessment of the effect of organic complexants on radionuclide transport through the use of a sorption reduction factor (SRF) that lowers the sorption distribution coefficient (K_d) is appropriate and is used by other safety cases.

The method used to estimate the concentration of the cellulose degradation product ISA is sound and is based on the latest understanding of ISA formation and its behaviour. The assessment is conservative as it ignores the possible effect of ISA degradation. The assessment also considers the effects of complexants such as EDTA and NTA present in waste that arise from decontamination processes. Data from the literature is used to estimate SRF and critical concentrations at which sorption is expected to be reduced by organic complexation.

There are a number of uncertainties in the assessment of the effects of organic complexants and these are explored in a specific calculation case that examines a ten-fold increase in SRF. This increase in SRF is may not however encompass the uncertainty in the radionuclide complexation effect. This is particularly important for Ni-59, which is the radionuclide contributing to the peak dose in the high concentration of complexing agents calculation case.

The review has highlighted a number of points for clarification from SKB which are provided in Appendix 2.

A subject area for further review by SSM is identified in Appendix 3 concerning pH buffering processes within waste package that is relevant to assumptions and requirements of the SR-PSU regarding the prevention of microbial activity by the high pH conditions of the SFR.

Suggestions are made regarding future research to further underpin the safety assessment, including a greater understanding of pH buffering and spatial heterogeneity and to reduce the uncertainties in the organic complexation of radionuclides, particularly isotopes of nickel.

Contents

1. Introduction

The Swedish Radiation Safety Authority (SSM) is undertaking a review of an application for the expansion of SKB's final repository for low and intermediate level waste at Forsmark (SFR). SKB's long-term safety analysis for the expanded repository is presented in a series of SR-PSU documents.

As part of SSM's review this assignment concerns the inventory of chemical substances in the waste and waste packaging. There are several general objectives for this assignment. Firstly, an understanding of SKB's handling of the inventory of chemical substances in the waste and waste packaging is achieved. Secondly an assessment of SKB's documentation is understandable and complete with regard to the information that is needed to be able to make an assessment of the application. Thirdly, an assessment is made of SKB's handling of chemical substances in waste and waste packages in detail, focusing on topics that will have a significant impact on the long-term safety of the repository and therefore also on the fulfilment of regulatory requirements.

There are a number of ways in which chemical substances in the waste and waste packaging could affect long-term safety, including:

- Enhancing the mobility of some radionuclides in groundwater by complexation with water soluble ligands derived from such chemical substances, which effectively reduce the effect of radionuclide sorption to solid materials in the engineered barrier system (EBS) and far field.
- Similar effects of colloids derived from chemical substances in the waste and waste packaging to which radionuclides may bind and thus reduce their sorption.
- Accelerating the degradation of the EBS, such as by the effect of chemical species on concrete degradation, which may enhance the rate of water flow through the waste and the sorption properties of the EBS.
- Providing a source of gas, such as by metal corrosion, radiolysis or microbial gas generation, this may act as a pathway for radionuclide transport and which may result in pressurisation that disrupts the repository.

The focus of this assignment concerns the review of the effect of aqueous complexants that result from chemical substances as this is represented explicitly in assessment calculations included in the SR-PSU. However, the assignment also considered other possible effects on long-term safety.

Further specific aspects of the assignment are:

- Identification of important chemical substances, included in the waste, in the matrix used or in the waste packaging.
- Among the identified chemicals, it has been considered if there are differences between the operational waste (existing waste in SFR) and decommissioning waste.
- Identify if, and how, SKB, has handled uncertainties for the important chemical substances in the waste, in the matrix, and the packaging.
- Identify if the distribution of chemical substances between and within the different rock vaults are addressed in SKB's application.
- Review how and in which parts of the application SKB have used the results of the chemical analysis and the impact of the identified substances.

This has been considered for the different vaults since waste, waste packaging, and barriers are more or less specific for each vault.
- A judgment is made whether SKB's documentation is sufficient when it comes to identifying the chemical substances present and if SKB has identified the processes that these chemicals contribute to within the repository related to the long-term safety of the repository.

In undertaking this assignment the following general points are made:

- The main SR-PSU documents identified by SSM have been reviewed to gain familiarity with SKB's approach and to identify further documents which are relevant to the inventory of chemical substances in the waste and waste packaging. The documents reviewed are listed in Appendix 1 and are further summarised in the following Section 2.
- The adequacy of relevant models, data and safety functions has been assessed as well as the handling of uncertainties. Comments are made regarding the merits and weaknesses of SKB's work.
- Suggestions for further complimentary information or clarifications that are deemed necessary to effectively assess the license application are made and are also listed in Appendix 2.
- The overall quality of SKB's documentation is assessed, including its structure, transparency, traceability, scientific soundness, as well as maturity of SKB's technical solutions and of SKB's methodology.

This report of the assignment is comprised of the following main sections:
- Section 2 summarises the main documents reviewed.
- Section 3 reviews the identification of chemical species of significance to long term safety and comments specific to the distribution of the inventory between compartments.
- Section 4 then reviews how SKB have assessed the effects of organic complexants and uncertainties in the effect on radionuclide transport.
- Section 5 provides comments on wider issues of potential relevance to the SR-PSU, including future research.
- Section 6 presents a summary and conclusions.
- The appendices provide summary information concerning the documents reviewed, suggestions for complimentary information and areas for further review.

In sections 3 and 4 a short summary of the SKB documentation is provided followed by reviewer's comments and **specific recommendations to SSM indicated in bold**, which are used to identify requests for complimentary information and areas for further review.

2. Key documents reviewed

In this section summary brief descriptions of SKB's reports that have been read and reviewed in the context of this assignment. Comments are provided on their significance to the review of chemical substances and whether they are understandable and complete with regard to the information that is needed to be able to make an assessment of the application. Appendix 1 provides a list of the documents.

2.1. Main Report TR-14-01

SKB report TR-14-01 is the main report of the SR-PSU. The summary of the report highlights significant improvements that SKB consider have been made since the previous assessment. This includes a more detailed study of cellulose degradation (Keith Roach et al, 2014); this report (R-14-03) has been recognised of importance to this review and is discussed in further detail in following sections of this report.

Section 3 of the TR-14-01 summary concerns the safety assessment, and notes that regarding internal processes within the repository system "Internal processes include thermal, hydraulic, mechanical and chemical processes that act in the repository system. Internal processes include, for example, groundwater flow and chemical degradation affecting the engineered barriers. Another example is production of gas as a result of corrosion of metals." Thus the effects of chemical substances in the waste and waste packages are recognised at a high level in the SR-PSU.

Section 4.2 of the TR-14-01 summary concerns requirements and constraints that arise from the assessment. These include "the requirement to maintain high pH in the waste form in order to minimise microbial activity, especially methanogens in the repository." Such a requirement may well be dependent on the chemical substances present in waste. Waste acceptance criteria (WAC) are also discussed in this section including the need for continued work and changes to WAC in areas of chemical reactivity (e.g. complexing agents) and gas evolution.

Sections 4.2 and 4.3 of TR-14-01 concern the initial state of the waste and the repository respectively and were highlighted by SSM in the scope of this review assignment. Section 4.2.1 describes the nature of operational waste, which mostly comes from the operation of the Swedish nuclear power plants. This includes ion exchange resins used to remove radionuclides from the primary cooling water of the reactors. Other waste materials arising from water clean-up include mechanical filter resin and precipitation sludge. Decommissioning waste comprises large quantities of scrap metal and concrete generated during decommissioning and dismantling of nuclear power plants. This will include the outer reactor pressure vessel (RPV) of boiling water reactors (BWR) that have sufficiently low activity to be disposed in SFR after decontamination. Such decontamination generates solutions that are cleaned with ion-exchange resins that are allocated to SFR. (It is not clear from TR-14-01 whether these decontamination solutions will contain complexing agents that will be disposed in SFR) Section 4.2.2 describes the material types present in operational waste, here resins and metals are described as both representing a large fraction of the inventory. Cellulose and other organic plastic wastes are described as being incinerated (with the ashes disposed at SFR) and the quantities of cellulose and these other organic disposed at SFR is small. The remaining subsections of Section 4.2. provide tabulated information regards the waste packages and masses of materials (waste and packaging). Whilst the key information is presented graphical summaries of this data for the Silo and various types of vault would have been beneficial to illustrate the proportion of the various chemical substances present.

Section 4.3 of TR-14-01 concerns the initial state of the repository and illustrates the design of the Silo and vaults in some detail. Other than describing the main types of materials used (concrete, macadam (crushed rock), bentonite) and providing background information about the Silo and vaults this section is not very informative to this review.

Section 7 of TR-14-01 describes the scenarios assessed within SR-PSU and which explore the role of safety functions of the repository that may be affected by internal processes. Section 7.4.6 concerns safety functions in the main scenario and includes discussion of the effect of sulphate on concrete degradation in the context of maintaining the safety function "low flow in waste vaults" which is monitored by the safety performance indicator *hydraulic contrast* (TR-14-01, page 224). Also the safety performance indicator *gas pressure* is recognised for the Silo. Both these indicators could be affected by chemical substances (e.g. sulphate in wastes, cellulose and metal gas generating substances and substances that may affect the pH and hence microbial activity) The safety function "good retention" is assessed with aid of the safety performance indicators: *pH, redox potential, concentration of complexing agents, available sorption surface area and corrosion rate*. The *concentration of complexing agents* indicator is of clear relevance and its discussion is based on that in Keith-Roach et al (2014, R-14-03) and considers disposed complexants, such as present in decontamination agents and the hyperalkaline cellulose degradation product ISA. Section 7.6 discusses less probable scenarios including an "accelerated concrete degradation scenario" and the "high concentrations of complexing agents scenario". The latter accounts for uncertainties in the amounts of complexing agents and cellulose in the repository by increasing the concrete sorption reduction factor (TR-14-01, Section 7.6.6). Results of these assessments are presented in Section 9 of TR-14-01 and these scenarios are further reviewed in Section 4 of this report.

Section 11. presents the conclusions, research needs and requirements of the SR-PSU. Section 11.4.3 concerns conclusions regarding the effect of internal processes on the evolution of the repository system and the analysis of radiological risks. The SR-PSU has shown that sorption is the main mechanism controlling radionuclide retardation. The SR-PSU recognises that waste consisting of organic materials (specifically cellulose) degrades into products that can form complexes with some radionuclides, which reduces their sorption. Section 11.5.1 presents conclusions regarding assumptions made in the SR-PSU that lead to requirements in controlling future wastes. This includes:

- The quantity of reactive metals related to gas generation.
- Assumptions regarding the maintenance of pH to minimise microbial activity so that C-14 release as methane gas will not be a dominant transport pathway.
- Limitations of the quantity of cellulose such that it does not give rise to high concentrations of ISA that adversely affect radionuclide sorption.

These requirements that relate to chemical substances present in the waste and waste packages.are defined in Section 11.5.2 and further discussed in Appendix I of TR-14-01.

Section 11.5.3 identifies additional research, Table 11-2 lists the following chemical processes in the waste form and packaging including; degradation of organic materials, microbial processes, metal corrosion and gas formation. Following text in this section identifies 10 research areas that relate to uncertainties across the whole SR-PSU. Research area 4. Gas formation discuses reactive metals, microbial gas generation (in BMA) with the goal to keep the amount of reactive metal low and to create unfavourable conditions for microbial activity.

2.2. Supporting SR-PSU reports reviewed

Several SKB reports referenced by the SR-PSU main report (TR-14-01) have been reviewed during the assignment.

TR-14-02, the Initial State Report, describes the nature of operational and decommissioning wastes disposed in SFR and describes the SFR Silo and vaults. TR-14-02 is the supporting reference for Section 4 of the main report discussed above.

TR-14-03, the Waste Process Report, describes the current scientific understanding of the processes in the waste and its packaging that have been identified in the Feature Events and Processes (FEPs) processing.

TR-14-04, the Barrier Process Report, describes the current scientific understanding of the processes in the engineered barriers that have been identified in the FEP processing as potentially relevant for the long-term safety of the repository.

TR-14-09, the radionuclide transport report, describes the radionuclide transport calculations carried out for the purpose of demonstrating fulfilment of the criterion regarding radiological risk. This report has provided useful information regarding how the effects of identified chemical substances in waste and waste packaging (organic complexing agents) have been represented in the assessment.

TR-14-10, the Data Report, qualifies data and describes how data, including uncertainties, that are used in the safety assessment are quality assured. This report has provided information regarding the audit trail of data used in the assessment calculations and further scientific arguments and justification of assumptions regarding the assessment of the effects of organic complexants and effects on radionuclide sorption.

R-15-15, Low and intermediate level waste in SFR, reference inventory for waste 2013, provides descriptions of the inventory and the quantities of wastes already stored in the repository as well as a forecast of future waste arisings.

R-14-01, Evolution of pH in SFR, which is the main supporting reference concerning the evolution of pH.

R-14-03, Assessment of complexing agent concentrations in SFR is an important underpinning reference to the main report (TR-14-01) concerning the approach to assessing the effects of complexing agents present in decontamination waste and that arising from the degradation of organic waste materials, most notably cellulose wastes. This report quantifies the concentrations of complexing agents in waste packages and individual vaults of the SFR.

2.3. General comments on document quality

Overall the SR-PSU documentation reviewed in this assignment is of good quality and is mostly clearly understandable. The document structure and hierarchy is appropriate for this type of safety assessment.

The main report (TR-14-01) does however contain a large quantity of detailed information and repeats much of what is presented in the supporting reports. In the case of the consideration of colloids it was found that the main report contained a fairly detailed discussion of colloids, but that a more thorough discussion was presented in the waste form and packaging process report (TR-14-03; Section 3.5.4) but this is not clearly referred to in the main report. Therefore, in some cases, little additional information has been obtained by reviewing the supporting TR reports.

Although in some cases the supporting reports have provided a more complete understanding.

The style of reports describing the individual rock vaults is repetitive and often the text is word for word identical. This makes it difficult to assess what the differences are between the vaults.

The Main report TR-14-01 appears to have a better level of referencing to specific sections or pages of underlying SKB reports than references between the underlying reports. In some cases referencing between SR-PSU reports is vague such as referring to other reports of many hundred pages without giving specific section or page numbers. For example the Data Report makes many general references to the Waste Processes Report, which cannot be traced easily. This makes it difficult to find underpinning information and justification. In other cases the underpinning referenced reports do not provide any further information. Some information is unpublished and not available for this review.

The reviewers consider that, despite some weaknesses, the documentation is sufficiently understandable and complete with regard to the information that is needed to be able to make an assessment of the application.

2.3.1. Specific comments on documentation

More specific comment on the presentation of specific documents, including formatting and editorial errors are provided here.

In several documents, e.g. TR-14-02, reference is made to the inventory report R-13-37, which is in Swedish. An English translation of this exists (R-15-15), so it would be clearer to refer to this document, rather than the Swedish inventory report, in reports written in English.

The strategy for allocation of different wastes to the SFR vaults (SKBdoc 1434623) is unpublished, but is referenced in the Initial state report (TR-14-02) , see later Section 3.10.

In TR-14-02, Page 54 appears to be missing. Page 50 appears twice, in the order p50, p51, p52, p53, p50, p55.

It might be helpful to have a description of the overall approach to emplacing different materials, such as bituminised waste or cellulose across the whole repository, rather than (or in addition to) describing their approach individually for each group of vaults, e.g. why the quantities of certain waste types are limited to different amounts across the different vaults.

In the Radionuclide Transport Report (TR-14-09) a graph (Figure 6-37) presenting dose from the **earthquake** calculation case is placed within the first page of Section 6.6 that discusses the high concentrations of complexing agents calculation case. A later figure appears to present the relevant data, but this poor formatting is a distraction for the reader.

3. Identification of chemical substances

This section of the review considers the approaches taken by SKB in identifying the presence and likely quantities of chemical substances either already-present in the waste materials, or generated via the degradation of the waste materials, that could affect the long-term radiological safety of the repository. Taking the effect of radionuclide complexation as an example, relevant chemical substances that are already present in the wastes include ethylene-diamine-tetraacetic acid (EDTA) and nitrilotriacetic acid (NTA) from decontamination processes, whilst relevant substances that could be generated by waste degradation include iso-saccharinic acid (ISA) from the degradation of cellulose.

The reference inventory document (R-15-15) provides the quantities of different waste materials already present in SFR1, as well as an estimate of the future quantities of decommissioning waste arisings in SFR3. The initial state report, TR-14-02, and the waste form and packaging process report, TR-14-03, detail the expected evolution of these waste materials within the repository and the expected degradation products that could impact on the long-term safety of the repository.

3.1. Ion-exchange resins

These will be present in the Silo and all other vaults except BRT and 2-5BLA (because they are present in operational, not decommissioning wastes). The organic ion-exchange resins are described as organic polymers with acidic or basic groups, making them capable of cation or anion exchange, in the form of powder or bead resins, dewatered and encapsulated in either cement or bitumen (or not at all), packaged in steel moulds, concrete moulds or steel drums. The most common resins are cation exchangers with a sulphonic acid functional group and anion exchangers with tertiary amines as the functional group (TR-14-01). Pages 155 – 156 of TR-14-01 summarise the potential mechanisms and products of ion-exchange resin degradation, by radiolytic, chemical or microbial mechanisms.

3.1.1. Radiolytic degradation

The reports recognise the potential for radiolytic degradation to generate sulphate ions (which could impact on the integrity of concrete structures within the repository) as well as oxalate (R-14-03) from cation exchangers and a range of amines, ammonia and nitrogen from anion exchangers. However, it is stated that radiolytic degradation is not expected due to the relatively low levels of radioactivity associated with the wastes, and in any case these degradation products would not be expected to impact on radionuclide sorption.

It is stated as a requirement of the existing Waste Acceptance Criteria (WAC) that the integrated dose received by encapsulated ion-exchange resins should not exceed 1 MGy (TR-14-02).

Reviewers' comments
The assumption regarding the radiation stability of cation exchangers is consistent with evidence in the literature, which confirms their resistance to degradation up to 10 MGy due partially to their aromatic nature. However, there is evidence that basic anion-exchange resins are less resistant to radiolytic degradation and that doses as

low as 0.1 MGy could cause degradation, releasing a range of amines and potentially hydrogen gas (Van Loon and Hummel, 1995; Traboulsi et al, 2013; Rebufa et al, 2015). This does not appear to have been considered in the SKB documentation.
It is recommended that SKB clarify the significance of the irradiation of basic anion exchange resins in the range 0.1 to 1 MGy based on literature and the consequence of released amines and hydrogen.

3.1.2. Chemical degradation

It is stated in the SR-PSU documentation that chemical conditions in SFR do not favour chemical degradation of the resins and this is not expected (TR-14-01).

Reviewers' comments
This is a valid argument, since addition polymers are generally not susceptible to alkaline degradation. However, for the dewatered, non-encapsulated resins the chemical conditions will be different, and it is not clear whether the potential for chemical degradation of resins in these conditions has been assessed. For instance functional sulphate and amine groups on the polymer structure may be more readily released. Potentially in untreated resins the ion exchange materials may undergo further exchange reactions with cations and anions in groundwater.

It is recommended that SKB clarify the degradation and ion exchange processes for dewatered, non-encapsulated resins.

3.1.3. Microbial degradation

The SKB documentation recognises the potential for aerobic and anaerobic microbial degradation of ion-exchange resins (R-14-03), but concludes that this will not occur to a significant extent under repository conditions.

Reviewers' comments
This conclusion is in agreement with recent studies that have not found clear evidence of microbial degradation of these materials under such conditions.

3.2. Complexing agents

The SKB documentation (R-14-03) identifies the following as potential complexing agents within the repository:

- Low molecular weight organic molecules EDTA, NTA, citrate, oxalate, gluconate
- Degradation products of cellulose (ISA)
- Cement additives
- Degradation products of polymers, bitumen and ion-exchange resins.

Inorganic ligands, e.g. CO_3^{2-}, NO_3^-, SO_4^{2-} etc. are not considered since it is concluded their complexation properties are not significant under the repository conditions.

Reviewers' comments
The identification of the types of potential complexing agents appears to be comprehensive and appropriate.

3.2.1. Complexing agents already present in the waste

Initially, organic complexing agents might be present within different waste forms. These chemicals originate from decontamination processes at the nuclear power plants. The data presented is partly based on new assessments of detergent use at the nuclear sites (R-14-03). The most important complexing agents used are identified as citrate, oxalate, NTA (and its derivatives), EDTA and gluconate.

The documentation states that chemical substances that can form mobile complexes with radionuclides should be avoided and are not suitable for disposal in SFR. These include (TR-14-02):

- N-carboxylated diamines, e.g. EDTA.
- N-carboxylated triamines, e.g. DTPA.
- N-carboxylated amino acids, e.g. NTA.
- Tricarboxylic acids, e.g. citric acid.
- α-hydroxi-carboxylic acids, e.g. glycone acid.

It is stated that EDTA use has been banned since 1998 and there are now more stringent limits in place on the disposal of complexing agents in SFR (R-14-03). It is also stated that complexing agents will not be present in the wastes produced at the nuclear power plants after 2012.

The quantities of complexing agents are based on information provided by power plants and other facilities producing waste to be disposed of at SFR.

Oxalate is expected to be solubility-limited by calcium oxalate to 10^{-5} M. Sorption of gluconate to cement phases is expected to reduce its concentration to < 10^{-9} M. Citrate concentrations will be relatively high, reaching almost 10^{-4} M within waste packages.

From experimental results obtained from literature, and the expected concentrations of complexing agents in the repository, it is concluded that Ni(II), Mn(II) and Pb(II) would be the only radionuclides to be complexed and that EDTA would be the only complexing agent of significance.

Section 7.6.6 of TR-01-01 presents a calculation case which considers higher concentrations of these complexing agents.

Reviewers' comments
There are several points for clarification regarding complexants in disposed waste highlighted in bold below.

It is not clear whether the chemical substances deemed "not suitable for disposal" are allowed under either the current WAC or the draft WAC for future decommissioning wastes. It is not clear what the more stringent limits on complexing agents are.

The justification for the absence of *all* complexing agents from wastes produced at the nuclear power plants after 2012 (R-14-03) is not clear. TR-01-01 states that SKB has restricted the use of *strong* complexing agents from 2011 onwards.

It would be useful to see in more detail how the quantities of complexing agents in the wastes has been calculated by the waste producers and supporting information to R-14-03 referenced.

The documentation states that the approach is to assess the total quantity of detergents used at a facility and divide the associated mass of complexant equally into all waste packages of a particular type, which seems to be a suitable and conservative approach. This produces an estimated total of 10 kg of EDTA that has been disposed at SFR up to 1998. This value seems low, considering the typical proportion of EDTA in decontamination agents that were in common use in the nuclear industry (at least those that have been used in the UK) and when comparing to the expected quantities of citric acid (1900 kg) and NTA (800 kg) (R-01-04). The original assessments that derived these values (SKB 99/10 and SKB 99/13) do not appear to be available in English to review.

Will decommissioning activities involve decontamination using reagents containing (non-EDTA) complexing agents that could enter the wastes? It is recognised that nuclear sites are modifying their choice of detergents, but can complexing agents realistically be eliminated from future wastes?

Appropriate literature data has been used to derive assumptions on the effects of EDTA on radionuclide behaviour in the repository, but there are gaps in the database (See further comments below in Section 4.1.2)

Degradation of the complexing agents themselves is not accounted for, but this represents a conservative approach.

3.2.2. Cellulose

Secondary decommissioning wastes consist mainly of cellulose (paper, cotton and wood) plus plastics and other materials. Cellulose will be present in the Silo and all other vaults except 2BTF and BRT. The amount of cellulose in future waste packages will be restricted by new WAC, which should be fully implemented by 2018.

In Table 3-15 of TR-14-02, a summary of the material quantities in the waste packages in the different waste vaults is given. The report states that the amounts of cellulose are expected to be overestimated in the prognosis.

Large quantities of cellulose are to be deposited in 2-5BLA. However, the mass of cellulose that will be deposited is highly uncertain as the wastes will be generated during the future decommissioning of plants, and steps may be taken to lower the cellulose content.

Whilst there will be no cellulose derivatives allowed in future grout formulations, the methoxycellulose additive Methocel has been used in the grout around the waste packages in the Silo and can degrade to form ISA. As such, it is considered as part of the cellulosic wastes.

Chemical Degradation
In R-14-03 there is a discussion of the mechanisms, rates and products of cellulose degradation, α-ISA being the most significant product because of its ability to form strong complexes with radionuclides.

It is stated that the cellulose in paper will be almost completely degraded (~100%) after 5,000 years; cotton degradation will be slower, with ~76% degraded after 5,000 years, and ~99% after 25,000 years.

Recent findings (Glaus and Van Loon, 2008) suggest that the assumptions of cellulose degradation rates in previous SFR reports (Fanger et al 2001) may have underestimated the potential ISA concentrations significantly, but that these have now been corrected.

Microbial Degradation
It is stated that microbes might utilise cellulose within the repository as an energy source (TR-14-02).

Reviewers' comments
The assumptions regarding cellulose degradation mechanisms and rates leading to ISA formation using recent literature data (Glaus and Van Loon, 2008) appear to be valid and appropriate and are an improvement over previous assessments.

The new cellulose degradation rate parameters (Glaus and Van Loon, 2008) are used to predict the extents of cellulose degradation at five time points: 10, 100, 500, 1,000 and 5,000 years (R-14-03 Section 3.3.1), **but it is not clear how these time points compare to the lifecycle of the repository**. Is time zero the moment the waste package is emplaced / the point of repository closure / the point of repository re-saturation / the point of package failure and ingress of alkaline water? The last option appears to be the most likely.

It is not clear why the estimates of cellulose quantities in Table 3-15 of TR-14-02 are expected to be overestimated.

The sentence in Section 3.4 of R-14-03 *"This applies the very pessimistic assumption for these vaults that the system will be "tight" over long periods of time"* explaining the calculation of ISA concentrations is unclear. **What is meant by "tight" and how is this a pessimistic assumption?**

It is stated that microbes might utilise cellulose within the repository as an energy source (TR-14-02), but the contribution of microbial degradation of cellulose in generating ISA does not appear to have been considered, presumably as a result of SKB's assumption that microbial action will be suppressed under repository conditions.

3.3. UP2 filter aid

UP2 filter aid is an important component of the organic waste materials present in SFR. It consists of polyacrylonitrile fibres with a chemical formula of $[C_3H_3N]_n$. It is expected to degrade to a range of carboxylic acids, amides, alkenes and ketones. However, "*UP2 will be conditioned in bitumen prior to disposal, which is likely to delay the onset of alkaline degradation for some time.*" (R-14-03; Section 2.2.2)

The documentation states that any degradation products of UP2 filter aid are not expected to affect radionuclide speciation and as such UP2 is not considered further.

Reviewers' comments
The discounting of UP2 degradation products appears to be based solely on the results of Duro et al (2012) and only results for Eu(III) are mentioned here. Were other radionuclides studied?

3.4. Bitumen

Whilst not a waste material in itself, bitumen is used to encapsulate a range of wastes, e.g. ion-exchange resins. Bituminised waste is present in the Silo, 1BLA and 1BMA. It will not be placed in 2BMA because of the use of non-reinforced barriers in this vault, which may be susceptible to bituminised waste swelling (TR-14-02). It is only placed in compartments to be backfilled with concrete grout to minimise any microbial degradation. The integrated dose to be received by bituminised wastes is not to exceed 10^6 Gy to avoid radiolytic degradation.

The documentation further states that bitumen is expected to change chemically over time under oxidising conditions, including via microbial degradation, but that this will be very slow under the anaerobic, low flow and high pH conditions. In any case, the chemical products of bitumen degradation under oxic conditions are reported to have weak or negligible complexing power.

The release of radionuclides from bituminised wastes is limited by the predicted rate of water uptake in bitumen (TR-14-02).

Reviewers' comments
Since irradiation of bitumen will be limited, it is reasonable to assume that its degradation will be very slow and limited by water diffusion and hydration of the material. Additionally, the assumption that its degradation products will not have significant complexing power at highly alkaline pH is in agreement with the literature. Oxalate is a strong complexant and a known radiolytic product of bitumen under aerobic conditions. However, such conditions are unlikely in SFR after closure and oxalate concentration should be solubility controlled

3.5. Evaporator concentrates

Dried salts from evaporator concentrates could cause swelling of some wastes in BMA upon resaturation (TR-14-01 Section 11.5.3). This is mitigated by emplacing the majority of these wastes in 1BMA, which is reinforced.

Reviewers' comments
The strategy of emplacing the majority of wastes containing evaporator concentrates in reinforced 1BMA is recognised, but a similar quantity (approximately half as much) is to be emplaced in 2BMA, which is not reinforced (TR-14-02 Table 3-15). It is stated elsewhere that bituminised wastes will not be placed in 2BMA because of the use of non-reinforced barriers in this vault, so it is not clear why the same exclusion does not apply to evaporator concentrates which are likely to undergo swelling. Swelling could damage the integrity of engineered barriers with consequences for radiological safety.

It is recommended that SKB clarify why evaporator concentrates do not require emplacement in reinforced barriers to manage swelling upon resaturation.

3.6. Reactive metals

There is Al(0) and Zn(0) metal present in some wastes (TR-14-02; Section 3.8). These will release hydrogen gas during corrosion, which could pressurise waste packages or regions of the repository vaults, risking the integrity of engineered barriers. Mitigation is achieved by minimising the quantities of reactive metals in the wastes. The need for further research in this area is recognised (TR-14-01; Section 11.5.3).

Reviewers' comments

The potential impacts of gas generation and waste swelling (bitumen and evaporator concentrates) should be subject to further assessment.

3.7. Organic cement additives

It is stated in TR-14-02 (Table 12-6) that Sika Plastiment (at 0.5%) and BV-40 Sika Retarder (at 0.05 – 0.2%) are used in the existing cement formulation, but that they will not be allowed in future grout.

Sikament 10, which is polymerised from N-vinylamides and derivatives of maleic anhydride, has been found to enhance the solubility of Pu and reduce its sorption to grout (R-14-03).

The methoxycellulose additive Methocel has been used in the grout around the waste packages in the Silo and can degrade to form ISA. As such, it is considered as part of the cellulosic wastes.

It is stated that the use of cement additives in SFR will be investigated at a later stage and is not considered further in the documentation.

Reviewers' comments

The superplasticiser substances could potentially act as radionuclide complexants and there does not appear to be an assessment of the possible impacts of superplasticisers in the existing grout materials at this time.

3.8. Other organics

Reviewers' comments

More detail on the expected nature of these materials would be useful. Whilst there is a description of their expected nature in the inventory report, R-15-15 (air filters, oil and combustible or non-combustible trash) and the waste form and packaging process report, TR-14-03 (halogenated and non-halogenated plastics and cable isolation) there does not appear to be an assessment of their expected degradation behaviour and potential impacts on the long-term safety. It is stated that these polymers will be resistant to degradation and unlikely to generate potential complexants. However, there does not appear to be an assessment of any additives present in these plastics, such as plasticisers, which can make up as much as 40% by mass in PVC films and are readily released under alkaline conditions (Smith et al, 2013). These species, e.g. phthalate esters, could potentially act as complexants for radionuclides, substrates for microbial activity or form non aqueous phase liquids if the quantities were sufficient.

It is recommended that SKB clarify the expected degradation behaviour of other organic materials.

3.9. Colloids

It is stated a number of times throughout the initial state report (TR-14-02) that colloids will not form within the concrete wasteforms and structures of the repositories due to the high ionic strength caused by Ca^{2+} ions. Further assessment of colloid formation and stability is provided in 6.3.7 and 6.3.8 of the main report (TR-14-01). This considers the potential for bitumen colloids to form, which is deemed likely, but that radionuclide association with them will be negligible. Bentonite colloids are not predicted to form for at least 1000 years after closure because of the Ca^{2+} concentrations in the interface between the bentonite and the shotcrete. A further discussion of colloids and the potential for their association with radioactivity and potential for transport is given in the waste form and packaging process report (TR-14-03). The general conclusions of these discussions are consistent.

Reviewers' comments

It seems reasonable to assume that within the highly alkaline porewater of the wastes that some colloids will be suppressed due to surface charge neutralisation and sufficient reference to relevant literature data is made. It would be helpful for the brief discussion of colloids in TR-14-02 to make reference to the more detailed discussions in TR-14-03 and TR-14-01.

3.10. Distribution of chemical substances between and within different rock vaults

The main report, TR-14-01, describes the functions of the repository engineered barriers and some of the differences between the different vaults and the Silo.

The engineered barriers are designed to achieve four main functions:

- limited advective transport via
    - hydraulic contrast for 1-2BMA and 1-2BTF where the permeable macadam backfill surrounding the concrete structures and the less permeable concrete structures enclosing the waste packages diverts water flow away from the concrete structures,
    - limited hydraulic conductivity for the Silo,
- mechanical stability (though this does not contribute directly to the long-term safety),
- sorption of radionuclides in 1–2BMA, 1–2BTF, Silo and BRT onto the concrete grout surrounding the waste packages, the concrete structures, the macadam outside the concrete structures and the plugs (the quantity of

cementitious materials is limited in 1BLA and 2–5BLA, so no sorption is credited in these vaults),
- favourable water chemistry (pH, redox potential and concentrations of complexing agents).

In the initial state report (TR-14-02, Section 3.7) the allocation of different waste types to different waste vaults is provided. The information is based on information on the waste produced by the end of 2012 and future predictions from the inventory report.

1BMA and 2BMA will contain intermediate level waste that has a lower dose rate or waste that is not suitable for deposition in the Silo. The waste contains solidified (bitumen or cement) ion-exchange resins and stabilised scrap metal and refuse. Small amounts of sludges and evaporator concentrates are also stored in 1BMA.

In 1-2BMA, all bituminised waste will be deposited in 1BMA to avoid the potential influence of waste swelling on the non-reinforced concrete barriers in 2BMA. Bituminised waste will also be present in the Silo and 1BLA. 1BLA does not have a reinforced concrete structure, similar to 1BMA. Instead, the rock walls are lined with shotcrete in 1BLA.

Reviewers' comments
The lack of credit for radionuclide sorption in 1BLA and 2-5BLA is recognised as a conservative approach for these vaults. These vaults contain the lowest activity wastes and are calculated to contain a total of 2.39×10^{12} Bq at closure of SFR, which is only around 0.2% of the total radionuclide inventory in SFR at closure (R-15-15).

It is not clear whether the other potential effects of the lower quantities of cementitious material have been considered, e.g. increased microbial activity and different chemical environment (affecting degradation rates etc.) due to the lower pH. There is a brief description of the expected evolution of pH in section 6.4.7 of TR-14-01, which is based on a modelling assessment (R-14-01). For 1BLA, it is expected that pH will return to the levels of intruding groundwater after approximately 19,000 years. This was a "simplistic stirred reactor tank approach for the examined compartments". This is described as conservative, which is likely the case for ISA formation from cellulose degradation, but the approach does not take account of localised regions of relatively low pH, which will likely form within waste packages and could result in enhanced microbial action leading to gas generation and other effects.

It is not clear why bitumen waste will be placed in 1BLA, but not 2BMA, neither of which have reinforced concrete structures to limit the effects of waste swelling. A similar question exists around the emplacement of evaporator concentrates (Section 3.5 of this document).

In the Inventory report (R-15-15), each vault in the repository is described, along with inventory information and for most, a brief section on waste placement within that vault, e.g. Section 6.4 in R-15-15, which refers to Table 6-4 detailing the distribution of waste packages within 1BMA until the end of 2012. The initial state report (TR-14-02) also provides a description of the allocation of waste types to different compartments in 1BMA. What is lacking, however, is a clear description of the rationale for the emplacement of different waste types both within vaults and between different vaults.

For the Silo, it is stated that the emplacement strategy is to place bituminised wastes in the centre of the Silo. For 1-2BTF and 1-5BLA, there is even less detail on the distribution of waste within these vaults in R-15-15.

Sections 1.3.1 and 1.3.2 in R-15-15 states that the waste emplacement strategy will consider long-term safety requirements. It is not clear what this strategy refers to, e.g. whether it is an existing strategy or one that is planned and how it is determined, except for the brief description below:

"For decommissioning wastes, systems that are calculated to have a specific radioactivity below 10^6 Bq/kg and do not require any specific radiation shielding will be deposited in BLA. Systems with higher specific radioactivity content will be deposited in BMA. BWR reactor pressure vessels are deposited in BRT. Ion exchange resins from system decontamination prior to decommissioning are deposited in the Silo. The distribution of waste between the existing and extended SFR is not yet established." (R-15-15).

In the Initial state report (TR-14-02), it is stated that the distribution of wastes follows the strategy for allocation of different wastes, SKBdoc 1434623 (unpublished).

Overall, it appears that a suitable approach is in place or planned for emplacing wastes between different vaults. However, it would be useful to have a published version of the strategy document (SKBdoc 1434623) for the allocation of wastes in order to assess the approach adopted. Currently, there is not sufficient information available to make an assessment of the distribution of chemical substances within waste vaults.

4. Treatment and assessment of uncertainties

In this section the assessment of the effects of chemical substances present in the waste and waste packages on radionuclide transport is reviewed. This aspect of the review is limited to the effects of organic complexants that are identified by SKB as the only chemical substances that are of sufficient significance for their specific consideration in assessment calculations.

The review firstly considers the general results of the main scenario radionuclide transport calculations (presented in TR-14-01 and TR-14-09) which identifies the key dose contributing radionuclides. Then the high concentrations of complexing agents scenario is discussed and the effects on the calculations considered.

4.1. Treatment in the main scenario

The main scenario safety functions are used to select and investigate less probable scenarios (TR-14-01, Section 5). The "good retention" safety function is assessed with aid of the safety performance indicator "concentration of complexing agents".

4.1.1. Estimation of complexant concentrations

Keith Roach et al (2014, R-14-03) detail the derivation of the quantities of complexing agents (i.e. complexing substance such as EDTA and NTA present in detergents) and cellulose, which forms the complexant ISA by hyperalkaline hydrolysis.

Table 3-1 of R-14-03 tabulates the masses of cellulose per waste package in 1 and 2BMA, the Silo and 1BTF. These masses of cellulose comprise several materials (paper, wood etc) and include a cement additive used in the Silo construction.

Table 3-2 of R-14-03 tabulates the mass of complexing agents per waste package in the SFR, subdivided into 1BMA 1, the Silo and 1 and 2BTF. This information is based on information provided by the nuclear power plants and other nuclear facilities.

The void and pore volume, and mass of hydrated cement in each SFR unit is estimated in R-14-03 in order to calculate a concentration of complexing agent and ISA formed by cellulose hydrolysis. The mass of cement is used to account for sorption of ISA and gluconate to cement. Concentrations of ISA are calculated considering a rate of hydrolysis based on data from long term (12 year) experiments. The α and β isomers of ISA are not represented specifically due to lack of isomer specific sorption data, although data for Eu indicates the α ISA forms stronger complexes. α ISA is less soluble than and β ISA, but both isomers are expected to have comparable sorption isotherms. ISA concentration is also limited by the formation of Ca-ISA. The solubility limit is assumed to be twice that of the solubility of Ca- α ISA and that both isomers are present in equal amounts. Concentration of ISA is calculated inside waste packages and including the packaging materials. In most cases ISA concentration attains the solubility limit of $2 \cdot 10^{-2}$ M by 1,000 years. ISA concentrations are also calculated for larger regions of the SFR vaults. The ISA concentrations remain below the expected solubility limit for α-ISA in all units considered when sorption is taken into account.
The Waste Process Report (TR-14-03) states that estimates of ISA concentration based on higher yield or ignoring sorption would give higher concentrations, but are judged as highly conservative.

The concentration of gluconate is modelled by considering the mass of gluconate in the inventory dissolved in pore water. Sorption of gluconate onto hydrated cement has been examined and has a large effect on gluconate concentration, decreasing the concentration from 10^{-4} - 10^{-5} M to 10^{-8} - 10^{-9} M. The high levels of gluconate sorption is based on studies by Glaus et al (2006).

The aqueous concentrations of all other complexing agents were calculated using the assumption that they remain in solution, with no sorption to hydrated cement.

The Waste Process Report (TR-14-03) lists concentrations derived by Keith-Roach et al (R-14-03):

EDTA, 7×10^{-7} M to 1×10^{-5} M
NTA, 2×10^{-4} M to 2×10^{-3} M
Citrate, 4×10^{-5} M to 9×10^{-4} M
Oxalate, 1×10^{-5} M (6×10^{-5} M to 1×10^{-4} M)
Gluconate, 3×10^{-10} M to 8×10^{-9} M

Comments are made in TR-14-03 that in the presence of calcium ions, some of these compounds may form solids that may limit their solubility.

Reviewer's comments
Information concerning the quantities of complexing agents in wastes provided by the waste producers does not have a reference, so the quantities of complexing agents cannot be validated (see also comments in Section 3). Information concerning the uncertainty in these estimates is not provided.

The assumptions regarding ISA concentration are conservative with regard to possible degradation processes. It is not clear whether the consideration of the α and β isomers of ISA together is a conservative approach to estimate ISA concentration since the concentration of β ISA could be above the assumed solubility limit. β ISA may be a weaker complexant of radionuclides than α-ISA, but this has only been examined for Eu and is subject to experimental uncertainties.

ISA concentrations calculated without the solubility limit are however presented (R-14-03, Figure 3‑2), these are around 1 order of magnitude higher than the solubility limit and can be used to estimate the concentration without solubility control. TR-14-03 views these concentrations as highly conservative, it appears that this may encompass higher concentrations of ISA examined in the high concentration of complexing agents calculation case. It would have been helpful if this was the case that it was stated in the documentation describing the calculation.

The concentrations for EDTA, NTA etc listed above in the TR-14-03 imply that additional effects of Ca solubility may apply to these data and to ISA. In fact the calculations by Keith-Roach include effects of solubility.

The estimate of pore volume and mass of hydrated cement in each SFR unit appears to include construction concrete as well as concrete within waste packages used to condition the waste and cement grout backfill around waste packages. The calculation of complexant concentration including the effect of sorption appears to consider the vaults as homogenous and that ISA that is generated in regions of waste can sorb on the whole mass of cement materials and can be diluted by water present in construction concrete. Furthermore the design of the vaults (e.g. BMA TR-14-01 Figure 4-7) includes the use of Macadam (crushed rock), which separates the waste from some construction concrete features. In the case of the Silo a diagram (TR-14-01 Figure 8-8) implies that water flow would only intersect a small proportion of the construction concrete, at the base and top of the Silo. Table B-3 of R-14-03 indicates that the Silo and BMA vaults comprise significant amounts of construction concrete.

SKB should clarify what construction concrete features in the SFR vaults are included in the calculations of complexant concentrations including packaging and justify the inclusion of construction concrete in these calculations in terms of considering these units as being homogeneous. Uncertainties in these calculations should also be assessed.

4.1.2. Consideration of the effect of complexants in radionuclide transport calculations

In the SR-PSU radionuclide transport may be retarded by processes of sorption of dissolved radionuclides onto solid materials in the EBS and the far field. The effect of sorption is represented by the sorption distribution coefficient (K_d) that is specific to each radionuclide and solid phases. The solid phase sorption substrates are hydrated cement grout, bentonite and crushed rock backfill present in the near field and the host rock in the far field (TR-14-10). The K_d for the cement phases changes with time to reflect the evolution of the cement materials. In the BLA vaults there is no cement phase present and there is no sorption . The effects of disposed organic complexants and ISA at the concentrations estimated by Keith Roach et al (2014, R-14-03) on the K_d are represented by a sorption reduction factor (SRF), which reduces the sorption effect onto hydrated cement.

The SRF are specific to each radionuclide and also to the concentration and type of complexant (see Data Report; TR-14-10). It is recognised (e.g. TR-14-10) that the effect of complexation on radionuclide sorption is complicated and includes effects related to the formation of Ca complexes and sorption of the organic complexants (TR-14-03, Section 3.5.3). Therefore, the potential impact of organic complexants is assessed as far as possible by defining limiting concentrations of organics below which no effects are expected. Complexation of radionuclides by ISA under high pH conditions has been quite widely studied but less data is available for other complexants. As much as possible, the limiting concentrations and reduction factors are based directly on experimental observations. However, to fill gaps in the experimental database, some analogies and approximations are used. Data for ISA complexation is summarised in Table 7-11a of TR-14-10 data for other ligands is in Table 7-11b of TR-14-10 and more conservative values are in Table 7-11c of TR-14-10. For most radionuclides SRF listed in these tables is increased by an order of magnitude for each order of magnitude increase in the complexant concentration.

The Data Report (TR-14-10, pages 105-107) provides a discussion of the experimental complexation data. On the basis of the available data, it is not possible to define a no-effect concentration for all organic ligands. Therefore, a cautious limit for ISA is selected that can be assumed to also cover the effect of the other organic substances. The extension to the other organic ligands takes into account the strong complexing ability of ISA as well as the conservative nature of the selected value (TR-14-10).

Reviewer's comments
The use of SRF to represent the effects of organic complexants in radionuclide transport calculations is a common approach in safety analyses (e.g. Heath and Williams, 2005; NDA, 2010a; Baston et al 2013).

The SRF and critical concentrations selected data for complexants other than ISA seem (from Table 7-11b of TR-14-10) to be based by analogy to ISA. There is limited data for EDTA/NTA complexation. The UK Low Level Waste Repository (LLWR) has recently assessed the effect of EDTA complexation under neutral pH and cementitious (pH 11) conditions (Baston et al, 2013). In general the SRF selected in this study for EDTA under pH 11 conditions at EDTA concentrations of 10^{-3} M and 10^{-5} M are consistent to those in Table 7-11b of TR-14-10. However, for nickel (Ni) and cobalt (Co) the LLWR study selected an SRF of 1000 for 1mM EDTA, given the strong complexation of divalent metals by EDTA. It should be noted that the LLWR study assessed Ni mainly as a non-radiological contaminant. For the SR-PSU it is stated that because of stable isotope exchange no complexation effect is expected and an SRF of unity is selected for the critical concentration. As discussed below Ni-63 is shown to be an important dose contributing radionuclide that is affected by complexation at the relatively low level of SRF selected.

It is recommended that SKB more clearly justify the SRF for Ni, including an explanation of how isotope dilution affects the selected SRF and critical concentrations of complexants listed in TR-14-10.

The effect of organic complexation appears to apply only to sorption onto cement grout: the SRF data are presented in Section 7 of the Data Report TR-14-10 that concern sorption onto cement; Section 8 of TR-14-10 concerns sorption onto rock contains no discussion of organic complexation. Whilst it is possible that some organic complexants may be subject to microbial degradation at lower pH conditions in rock materials this uncertainty does not appear to be discussed in the SR-PSU. In addition, dilution and competition effects by cations present in groundwater may reduce the complexation effect; however a discussion of these effects could not be found in the SR-PSU.

It is recommended that SKB clarify if the effects of organic complexation on radionuclide transport through crushed rock and the host rock is represented in the SR-PSU and to justify their approach to this subject.

4.2. Treatment in the high concentrations of complexing agents calculation case

As described above the main scenario considers the effects of complexing agents on sorption for what are presumed to be best estimates of the pore water concentrations of complexants (R-14-03) and effect on radionuclide sorption (critical concentrations and SRF; TR-14-10). Uncertainty in the concentration of complexants is explored in the high concentrations of complexing agents calculation case (Section 6.6 of TR-14-09).

The calculation accounts for uncertainties in the amount of complexing agents and cellulose in the repository. Higher sorption reduction factors than in the global warming calculation case are applied to reflect chemical conditions with higher concentrations of complexing agents. Only radionuclides whose sorption properties are potentially affected by organic complexing agents are attributed the reduction factor for the partitioning coefficient in waste vaults actually containing organic complexing agents (1BMA, Silo, 2BMA, 1BTF and 2BTF). The waste vaults, 1BLA and 2–5BLA, where sorption is not included in the model, are not affected by this calculation case (TR-14-09). In the calculations, the concrete sorption reduction factor used was increased by a factor of 10 compared with the global warming calculation case. This factor was chosen because reduction factors are estimated to increase by a factor of 10 with each 10-fold increase in the concentration of complexing agent above the indicated no-effect level given in the Data report (TR-14-10).

Reviewer’s comments
This calculation case accounts for a 10 fold increase in inventory of cellulose and disposed complexing agents. This seems robust in terms of assessing the uncertainty in cellulose content and the concentration of NTA, which is estimated to be present in significant concentrations (~10^{-2} M; R-14-03). The case represents a pragmatic approach to assess the uncertainty in several different complexing agents and is less effective at examining the uncertainty in the very strong complexing agent EDTA which is considered to be present in low amounts (10kg in the whole repository).

The case does not assess the uncertainty in the critical concentrations of complexants or the SRF (listed inTR-14-10). In contrast to the inventory and resulting porewater concentrations these chemical parameters are likely to be subject to a much larger range of uncertainty than is captured in the 10 fold increase in SRF.

This is particularly so for complexants other than ISA for which very little experimental data has been presented in TR-14-10.

It is recommended that SKB further justify the 10 fold increase in SRF in respect to uncertainty in the critical concentration levels and complexation effects of all complexants.

4.3. Results of the radionuclide transport assessment

The results of the assessment calculations presented in TR-14-01 and TR-14-09 indicate that Mo-93 is the main contributor (57.7% of peak dose) to dose with organic C-14 also significant (17.9 % of peak dose, TR-14-09, Figure 5-4, Table 5-1). Dissolved Mo-93 will be present as in the repository as the molybdate anion and is assumed to be non-sorbing (TR-14-10). Similarly organic C-14 is assumed to be non-sorbing.

In the high concentrations of complexing agents calculation case the dose resulting from Ni-59 increases significantly after around 10,000 years. The peak dose in this case results from Ni-59 (75.7 % of dose; TR-14-09 Table 6-39) and is a factor of two high than the global warming case (main scenario) and occurs later at 44,500 AD. Figure 6-38 of TR-14-09 indicates that the dose from Ni-59 increases by one order of magnitude by the effect of reduced sorption due to complexing agents. The radionuclides that are the main contributors to dose in the main scenario (Mo-93, C-14-org, U-238, I-129, Cl-36 and U-235) are stated as being unaffected by organic complexation.

Reviewer's comments
Given that organic complexation is assessed by its effect on reducing sorption and that the main dose contributors (Mo-93 and organic C-14) are non-sorbing species it is expected that organic complexation will not have an effect on dose in the main scenario.

The comments that U-238 and U-235 are not affected by organic complexation (TR-14-01, TR-14-09) is misleading since uranium can form complexes with ISA and other organic complexants as discussed in the Data Report (TR-14-10). The reason why these radionuclides are not affected in the assessment is because the majority of uranium is located in the BLA vaults, which do not contain significant amounts of hydrated cement and thus are assumed to be non-sorbing. This behaviour and interpretation could have been explained more clearly.

The increase in dose in the high concentrations of complexing agents calculation case that results from Ni-59 indicates a roughly linear order of magnitude increase in dose from Ni-59 for an order of magnitude decrease in the K_d for sorption onto cement in the near field. Given uncertainties in the effect of Ni complexation and the low SRF (unity) compared to other metallic radionuclides then it is possible that organic complexation could have a more significant effect on the peak dose, which would likely exceed the risk criterion (TR-14-09; Figure 6-39).

It is recommended that SKB provide further discussion of the uncertainties in their handling of the effect of organic complexation of Ni and the implications for dose calculations.

5. Further review comments

In this section wider aspects of the SR-PSU are discussed with regard to the handling of chemical substances in waste and waste packaging that could impact on safety.

As highlighted in the Introduction there are several ways in which chemical substances can affect the safety of a repository for LLW/ILW, including direct effects on radionuclide transport in groundwater, effects on the EBS affecting water transport and processes related to gases. The SR-PSU has considered a quite wide range of chemical interactions and processes, but has focussed on effects related to the complexation of radionuclides. This approach is appropriate given the inventory of organic complexing agents present in existing disposed waste and the inventory of cellulose, which has the potential to form ISA under the hyperalkaline conditions resulting from the use of concrete materials.

An underpinning assumption that relates to the expected high pH conditions of the SFR is that the high pH (> pH 12.5, e.g. buffered by $Ca(OH)_2$) inhibits microbial activity. The principal reasoning here appears (from TR-14-01) to be related to the prevention of the development of methane generation, which could provide a gaseous pathway for the transport of C-14 to the biosphere. TR-14-01 states that: "As the pH of the system controls the microbial activity to great extent, extensive microbial activity will not occur until pH has dropped to optimum pH for microbial activity. Nevertheless, the pH in the repository will still be unfavourable for microbial activity during this period. The time scale or time scales on which microbial processes occur is related to the amount of available nutrients and energy sources in the system."

The main report (TR-14-01; Section 6.4.7) describes how the modelling uses a **simplistic stirred reactor tank** approach for the examined compartments, Silo wall, Silo waste domain, 1BMA wall, 1BMA bitumen-conditioned waste compartment, 1BMA concrete-conditioned waste compartment, 2BTF, 1BTF and 1BLA. Furthermore it is emphasised that the method is an approximate and conservative approach used solely to determine the **global average** pH evolution. Substantial local deviations are expected due to the inhomogeneous character of the waste compartments, flow path restrictions etc. As noted in Section 3.10 of this assignment report the BLA vaults have lower pH buffering capacity as a result of the lower cement content.

Reviewer's comments
The pH modelling (R-14-01) undertaken on a large scale cannot represent the processes occurring within waste packages, where pH could vary depending on the inhomogeneity between cellulose materials and cement grout. The modelling does take some account of the reactions (acidity) generated by the ion exchange reactions and degradation of organic wastes (resins, and cellulose). However for cellulose only the deprotontaion reaction of ISA is considered (R-14-01, Section 3.10). The possibility exists that in some low pH niches complete degradation of cellulose to form CO_2 will occur, which would yield additional protons for the same mass of cellulose. This more conservative approach to consider the acidity generated by cellulose degradation on pH is adopted by other safety cases (NDA. 2010b). Further acidity could be generated by other organic wastes such as polyvinyl chloride (PVC) which can release HCl (NDA, 2010b).

Such localised effects on pH buffering within waste packages could lead to lower pH conditions than predicted by the stirred reactor modelling approach. This could allow microbial processes to develop resulting in complete degradation of cellulose to CO_2 and the generation of greater levels of acidity than currently considered in the modelling (R-14-01).

It is recommended that SKB consider how pH might evolve at the waste package scale considering the spatial distribution and quantities of cellulose in waste packages and full oxidation to CO_2.

Such consideration and modelling of processes at smaller scales should yield a more realistic understanding of the likelihood and effect of the microbial processes occurring in SFR. However, it is not clear if these interrelated processes are conservative or not:

- The current homogeneous approach of modelling pH evolution may be conservative with respect to the formation of ISA and the degradation of complexing agents which can enhance radionuclide mobility in groundwater.
- However it is unlikely to be conservative with respect to methane generation and the transport of C-14 in gas. This aspect will need to take account of the inventory of C-14 in different waste materials and the potential of the wastes to affect pH buffering and microbial gas generation.

It is recommended that SKB clarify and discuss the balance of impacts that are affected by the assumptions regarding pH evolution and homogeneity; (1) though groundwater where dose may be enhanced by the formation of ISA at high pH and (2) the generation of methane gas and the possible release of ^{14}C that may occur in low pH regions of waste but, where lower concentrations of ISA may develop.

This clarification may have a bearing on the stated requirements and constraints that arise from SR-PSU that include the requirement to maintain high pH in the waste form in order to minimise microbial activity.

5.1. Comments on future research

Section 11.5.3 of the main report (TR-14-01) identifies ten areas of future research related to waste form and packaging, engineered barriers and geosphere. Areas of research related to the waste form are highlighted in Table 11-2 of TR-14-01 and include:

- Degradation of organic materials
- Microbial processes
- Metal corrosion
- Gas formation

The degradation of organic materials including the formation of complexing agents is of key importance to the assessment of radionuclide transport and effects on sorption. It is also relevant to the maintenance of high pH buffering that is a key requirement that arises from the SR-PSU. The four areas of research are quite closely related and are also related to pH buffering.

Given the requirement regarding pH buffering it would seem sensible that a research topic examining the spatial heterogeneity in pH buffering were considered.

It is notable that no specific research area relates to uncertainties and the existing knowledge gaps regarding organic complexation of radionuclides by ISA or disposed complexing agents. As discussed in Sections 4.1.2 and 4.2 of this assignment report there is little data concerning the effect of complexants other than ISA on radionuclide sorption. Considering the results of the assessment of the high concentrations of complexants calculation case (Section 4.3) complexation data and sorption studies concerning Ni complexation would seem most appropriate given the potential impact on dose.

6. Conclusions and summary

This document has provided a review of the inventory of chemical substances in the waste and waste packaging of SFR as presented in the SR-PSU. The review firstly considered how SKB have identified chemical substances that could affect long-term safety. Then the review has examined how the uncertainties in the amounts and effects of these substances on radionuclide transport have been assessed. Within these review topics an assessment of SKB's documentation has been made with regard to the understanding and completeness required to make an assessment of the application.

The main conclusion of the review is that SKB have identified the main chemical substances (cellulose and disposed organic complexants) that could affect radionuclide transport from the SFR wastes and waste packing. The method of assessment of the effect of organic complexants on radionuclide transport through the use of a sorption reduction factor (SRF) that lowers the sorption distribution coefficient (K_d) is appropriate and is used by other safety cases.

The application of the assessment method to estimate the concentration of the cellulose degradation product ISA is sound and is based on latest understanding of the rate of alkaline cellulose hydrolysis, ISA sorption and solubility. The assessment is conservative as it ignores the possible effect of ISA degradation. The assessment also considers the effects of complexants such as EDTA and NTA present in waste that arise from decontamination processes. The concentration of these substances is based on records from waste consignors and ignores degradation processes. Data from the literature is used to estimate SRF and critical concentrations at which sorption is expected to be reduced by organic complexation.

There are a number of uncertainties in the assessment of the effects of organic complexants and these are explored in a specific calculation case that examines a ten-fold increase in SRF. This increase in SRF is likely to encompass the possible uncertainty in the estimates of complexant concentration, but it may not encompass the uncertainty in the radionuclide complexation effect. This is particularly important for Ni-59, which is the radionuclide contributing to the peak dose in the high concentration of complexing agents calculation case. Ni is allocated an SRF of 1 in the main assessment (increased to 10 in the calculation case). Higher increases in SRF would likely exceed the risk criterion.

Overall the SR-PSU documentation reviewed in this assignment is of good quality and is mostly clearly understandable. The document structure and hierarchy is appropriate for this type of safety assessment. The main report (TR-14-01) does however contain a large quantity of detailed information and repeats much of what is presented in the supporting reports. Referencing between documents could be improved giving more specific section references. There are a few formatting errors in the documents.

Section 5 of this document discusses some further effects of organic chemical substances that could be potentially important to the SR-PSU in terms of the assumption regarding the maintenance of high pH conditions that inhibit microbial processes. Specifically, the models of pH evolution and buffering cannot take account of the localised occurrence of low pH niches, such as in waste packages containing cellulose, where microbial activity could occur resulting in the complete oxidation of cellulose to CO_2 leading to accelerated loss of pH buffering. This could of course also impact on assumptions in the SR-PSU regarding methane gas formation. This subject is suggested as an area for further review by SSM (Appendix 3).

Suggestions are made regarding future research to further underpin the safety assessment, including a greater understanding of pH buffering and spatial heterogeneity and to reduce the uncertainties in the organic complexation of radionuclides, particularly isotopes of nickel.

6.1. Complementary information

The review has highlighted a number of points for clarification regarding the identification of the chemical substances, which have been highlighted in Section 3 of this report and are listed in Appendix 2. These points (Appendix 2 points 1 to 6 inclusive) include comments on the following general areas:

- Ion exchange resin degradation
- Disposed organic complexants
- Cellulose degradation
- Evaporator concentrates
- Other organic substances

Further points for clarification regarding the assessment of the effect of organic complexants are highlighted in Section 4 and again listed in Appendix 2. These points (Appendix 2 points 7 to 11 inclusive) include comments on the following general areas:

- The consideration of concrete features of the SFR vaults in the calculation of complexant concentrations.
- The SRF for Ni
- The effect of organic complexation on radionuclide transport through the far field.
- Representation of uncertainty in radionuclide complexation effects in the SRF parameter.
- The implications for Ni complexation on dose calculations.

In addition two further points for clarification are highlighted in Section 5 (Appendix 2 points 12 and13) concerning wider issues related to pH evolution and spatial heterogeneity.

7. References

Baston, G.M.N., Berry, J.A., Heath, T.G. and Hunter, F.M.I. (2013) LLWR Environmental Safety Case: Review of the Impact of EDTA and Related Complexants on Contaminant Sorption and Solubility. LLWR/ESC/SPE(12)098, AMEC/006357/001 Issue 8. http://llwrsite.com/wp-content/uploads/2013/11/006357-001-Review-of-Impact-EDTA-Related-Complexants-Sorption-and-Soluability-v8-MASTER-26-09-13.pdf

Duro L, Grivé M, Gaona X, Bruno J, Andersson T, Borén H, Dario M, Allard B, Hagberg J, Källström K, 2012. Study of the effect of the fibre mass UP2 degradation products on radionuclide mobilisation. SKB R-12-15, Svensk Kärnbränslehantering AB.

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NDA, (2010b) Geological Disposal: Near field evolution status report, Nuclear Decommissioning Authority Report NDA/RWMD/033.

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Smith, V., Magalhaes, S., Schneider, S., (2013) The role of PVC additives in the potential formation of NAPLs. Report to NDA RWMD. AMEC/PPE-2834/001.

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APPENDIX 1

Coverage of SKB reports

The following reports have been covered in the review:

Reviewed report	Reviewed sections	Comments
SKB TR-14-01 Safety analysis for SFR Long-term safety: Main report for the safety assessment SR-PSU	Summary, Sections; 4.2, 4.3, 5, 6.3.7, 6.3.8, 6.4.7, 7.46, 7.6.6, 9.3.6, 11.4.3 11.5.1, 11.5.2, 11.5.3, Appendix I	Main report, generally the most useful source of information, sometimes containing more information than underpinning reports.
SKB TR-14-02 Initial state report for the safety assessment SR-PSU	All sections	Describes the nature of operational and decommissioning wastes disposed in SFR. It is the supporting reference for Section 4 of the main report.
SKB TR-14-03 Waste form and packaging process report for the safety assessment SR-PSU	All sections	Describes the current scientific understanding of the processes in the waste and its packaging that have been identified in the Feature Events and Processes (FEPs).
SKB TR-14-04 Engineered barrier process report for the safety assessment SR-PSU.	Used as background information	Describes the current scientific understanding of the processes in the engineered barriers. This was not particularly relevant for the review.
SKB TR-14-09 Radionuclide transport and dose calculations for the safety assessment SR-PSU	Sections 4,5 and 6	This report has provided useful information regarding how the effects of identified chemical substances in waste and waste packaging (organic complexing agents) have been represented in the assessment.
SKB TR-14-10 Data report for the safety assessment SR-PSU. SKB	Sections 7 and 8	Important reference for the effects of complexing agents on radionuclide sorption
SKB R-15-15 Low and intermediate level waste in SFR:Reference inventory for waste 2013	Sections 1 - 9	Provides descriptions of the inventory and the quantities of wastes already stored in the repository as well as a forecast of future waste arisings.
SKB R-14-01 Evolution of pH	All sections	The main supporting reference

in SFR 1		concerning the evolution of pH.
SKB R-14-03 Assessment of complexing agent concentrations in SFR	All sections	Key underpinning reference concerning the concentration organic complexation agents

APPENDIX 2

Suggested needs for complementary information from SKB

1. It is recommended that SKB clarify the significance of the irradiation of basic anion exchange resins in the range 0.1 to 1 MGy based on literature and the consequence of released amines and hydrogen.

2. It is recommended that SKB clarify the degradation and ion exchange processes for dewatered, non-encapsulated resins.

3. There are several points for clarification regarding complexants in disposed waste:
    a. It is not clear whether the chemical substances deemed "not suitable for disposal" are allowed under either the current WAC or the draft WAC for future decommissioning wastes.
    b. It is not clear what the more stringent limits on complexing agents are.
    c. The justification for the absence of all complexing agents from wastes produced at the nuclear power plants after 2012 (R-14-03) is not clear
    d. It would be useful to see in more detail how the quantities of complexing agents in the wastes has been calculated by the waste producers and supporting information to R-14-03 referenced.
    e. Will decommissioning activities involve decontamination using reagents containing (non-EDTA) complexing agents that could enter the wastes?

4. The following points for clarification regard cellulose degradation
    a. It is not clear why the estimates of cellulose quantities in Table 3-15 of TR-14-02 are expected to be overestimated.
    b. The sentence in Section 3.4 of R-14-03 "This applies the very pessimistic assumption for these vaults that the system will be "tight" over long periods of time". What is meant by "tight" and how is this a pessimistic assumption?

5. It is recommended that SKB clarify why evaporator concentrates do not require emplacement in reinforced barriers to manage swelling upon resaturation.

6. It is recommended that SKB clarify the expected degradation behaviour of other organic materials.

7. SKB should clarify what construction concrete features in the SFR vaults are included in the calculations of complexant concentrations including packaging and justify the inclusion of construction concrete in these calculations in terms of considering these units as being homogeneous. Uncertainties in these calculations should also be identified and assessed.

8. It is recommended that SKB more clearly justify the SRF for Ni, including an explanation of how isotope dilution affects the selected SRF and critical concentrations of complexants listed in TR-14-10.

9. It is recommended that SKB clarify if the effects of organic complexation on radionuclide transport through crushed rock and the host rock is represented in the SR-PSU and to justify their approach to this subject.

10. It is recommended that SKB further justify the 10 fold increase in SRF in respect to uncertainty in the critical concentration levels and complexation effects of all complexants.

11. It is recommended that SKB provide further discussion of the uncertainties in their handling of the effect of organic complexation of Ni and the implications for dose calculations.

12. It is recommended that SKB consider how pH might evolve at the waste package scale considering the spatial distribution and quantities of cellulose in waste packages and the full oxidation to CO_2.

13. It is recommended that SKB clarify and discuss the balance of impacts that are affected by the assumptions regarding pH evolution and homogeneity; (1) though groundwater where dose may be enhanced by the formation of ISA at high pH and (2) the generation of methane gas and the possible release of ^{14}C that may occur in low pH regions of waste but, where lower concentrations of ISA may develop.

APPENDIX 3

Suggested review topics for SSM

1. The pH buffering and evolution of the SFR vaults should be reviewed to consider the effects of the spatial distribution of acid producing organic wastes e.g. cellulose. Such a review should focus on the scale of processes within waste packages and draw conclusions with regard to the prevention of microbial processes. The further implications for long term safety should also be included.

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The Authority reports to the Ministry of the Environment and has around 300 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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