R-08-130

Safety analysis SFR 1

Long-term safety

Svensk Kärnbränslehantering AB

December 2008

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Preface

This report is a translation of the long-term safety analysis report for the repository for low- and intermediate-level waste, SFR. The English translation is intended to enable a wider distribution and review of the material. SKB's license to operate the facility is based on the Swedish version of the report, which has been reviewed in accordance with SKIFS 2004:1.

The Swedish regulatory authorities (SKI and SSI) were reorganized during 2008, after this report was produced in its Swedish version. This is therefore not taken into account in the translation. Today the sole regulatory authority in the field of nuclear safety and radiation protection is the Swedish Radiation Safety Authority – SSM (Strålsäkerhetsmyndigheten).

Not all references found in this report are publicly available, but those supporting the safety case in the report are.

Stockholm, December 2008

Anna Gordon
Project leader, SFR 1 SAR-08

Contents

1 Introduction

An updated assessment of the long-term safety of SKB's final repository for radioactive operational waste, SFR 1, is presented in this report. The report is included in the safety analysis report for SFR 1. The most recent account of long-term safety was submitted to the regulatory authorities in 2001 /SKB 2001a/. The present report has been compiled on SKB's initiative to address the regulatory authorities' viewpoints /SSI/SKI 2003/ regarding the preceeding account of long-term safety.

A safety assessment consists of several steps. An important step is identifying and treating scenarios (i.e. probable future courses of events of importance for the long-term evolution and safety of the repository) in a structured manner. SKB recently carried out a safety assessment that deals with final disposal of spent nuclear fuel in a deep geological repository, SR-Can /SKB 2006a/. Safety functions and safety performance indicators (called "safety function indicators") are used in SR-Can to identify which scenarios are relevant for assessing the long-term safety of the repository. The same method has been applied as far as possible in the execution of this safety assessment for SFR 1.

Besides the new mode of working with safety functions there is another important difference between the 2001 safety assessment and the current assessment: The time horizon in the current assessment has been extended to 100,000 years in order to include the effect of future climate changes.

The safety analysis report SAR-08 for SFR 1 covers both the operating phase and the post-closure phase. It consists of five main parts:

- General Part 1, Facility design and operation
- System descriptions
- Type descriptions for different waste categories
- General Part 2, Long-term safety
- Safety-related technical specifications, STF

In addition there is a part where all references of importance for General Parts 1 and 2 are presented. The overall report structure for the integrated safety analysis report can be found in Chapter 1 of General Part 1, "Facility design and operation" (in Swedish).

1.1 Purpose

The purpose of this renewed assessment of the long-term safety of SFR 1 is to show with improved data that the repository is capable of protecting human health and the environment against ionizing radiation in a long-term perspective. This is done by showing that calculated risks lie below the risk criteria stipulated by the regulatory authorities.

1.2 Background

1.2.1 Purpose and design of the facility

The final repository for radioactive operational waste, SFR 1, is located in Forsmark in northern Uppland in the immediate vicinity of the Forsmark nuclear power plant, see Figure 1-1.

Figure 1-1. *Overview of the surface part of the facility at the harbour in Forsmark.*

SFR 1 is built to receive, and after closure serve as a passive repository for, low- and intermediate-level radioactive waste. The disposal chambers are situated in rock beneath the sea floor, covered by about 60 metres of rock. The underground part of the facility is reached via two tunnels whose entrances are near the harbour. The repository has been designed so that it can be abandoned after closure without further measures needing to be taken to maintain its function.

The low- and intermediate-level waste in SFR 1 consists of operational waste from the Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, as well as similar radioactive waste from other industry, research institutions and medical care. Waste that is disposed of in SFR 1 belongs to the category 2.1, i.e. short-lived waste, in accordance with the IAEA's definition /IAEA 1994/. Category 2.1 is waste with restricted long-lived radionuclide concentrations (limitation of long-lived α-emitting radionuclides to 4,000 Bq/g in individual waste packages and to an overall average of 400 Bq/g per waste package /IAEA 1994/.

The various parts of the repository are designed to accommodate the different types of containers and materials that occur and to provide adequate protection depending on the activity levels present in different types of waste, see Figure 1-2 and Figure 1-3. For more information on waste containers present in SFR 1, see Chapter 6 in General Part 1, "Facility design and operation". Activity levels and waste types in the different parts of the repository are shown below.

- Silo – for intermediate-level, solidified waste.
- BMA – for intermediate-level, mostly solidified waste.
- 1BTF and 2BTF – for dewatered and relatively low-level ion exchange resins.
- BLA – for low-level solid waste such as trash and scrap.

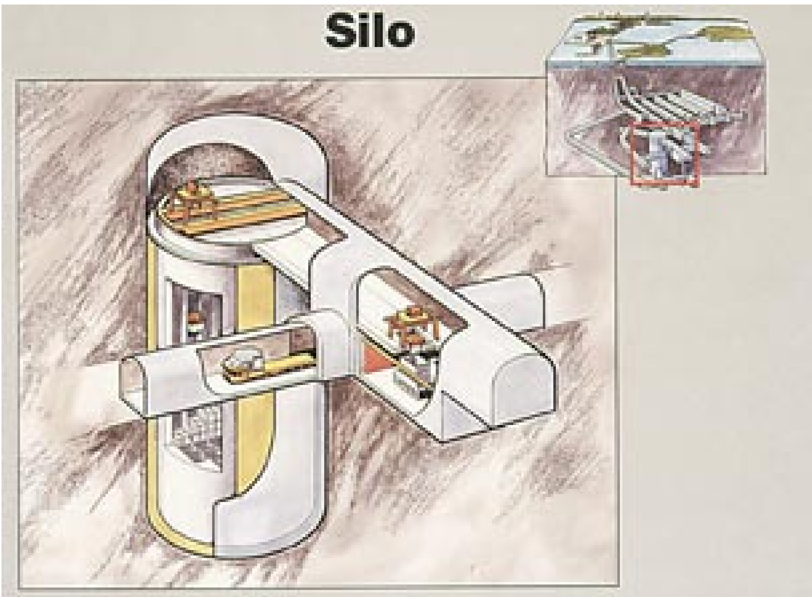


Figure 1-2. SFR 1, the silo: height 69.5 m, diameter 29.5 m.

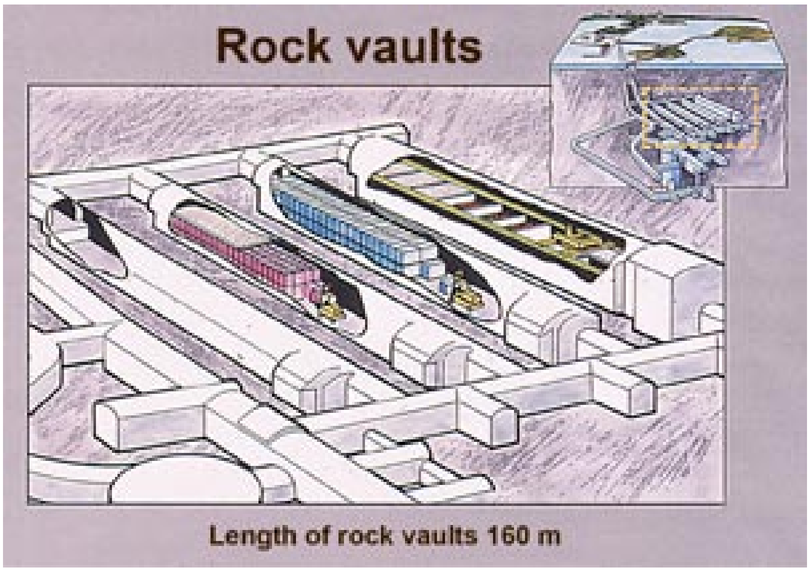


Figure 1-3. SFR, the rock vaults. Shown from left to right are the chambers for 1BTF, 2BTF, BLA and BMA.

1.2.2 The toxicity of the waste

The waste in SFR 1 is short-lived low- and intermediate-level waste. The decay of the activity of the waste from the time of closure of the repository up to around 100,000 years after closure is depicted graphically in Figure 1-4. After 100 years the activity is less than half, and after 1,000 years only about 2% of the original activity remains.

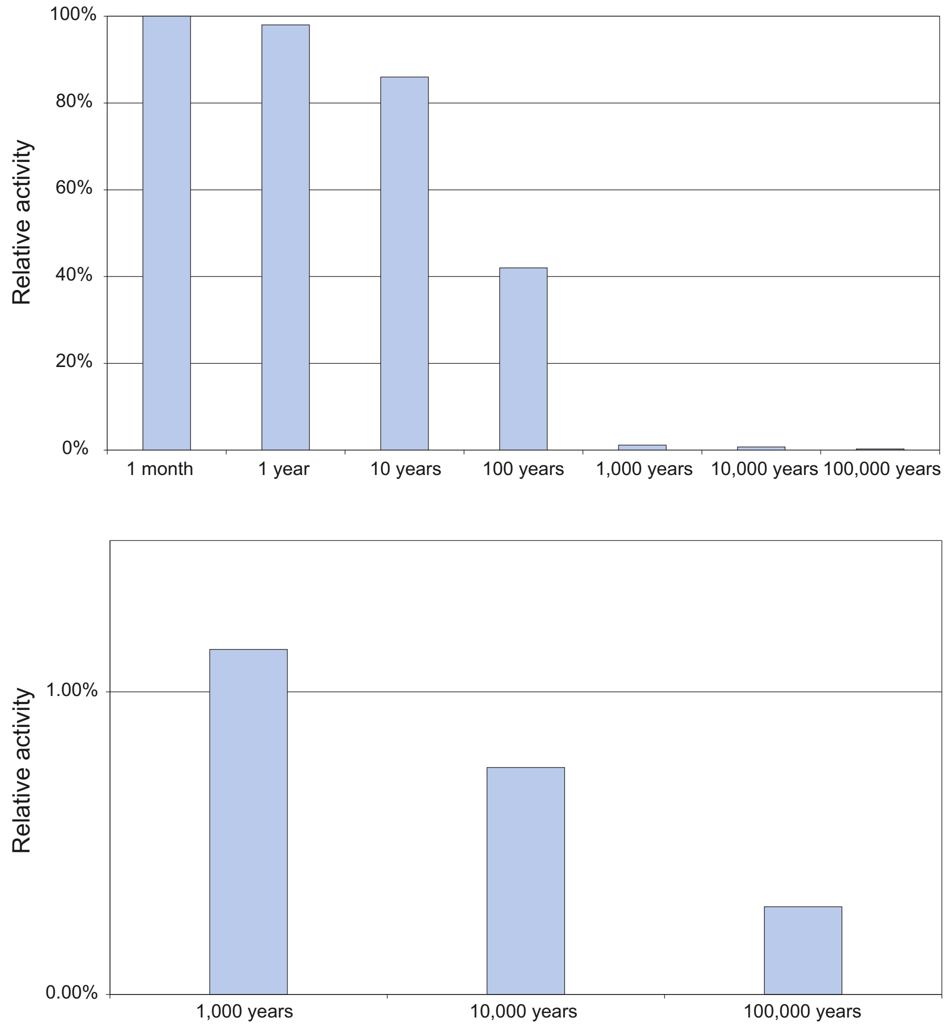


Figure 1-4. *Relative activity of the waste in SFR 1 at different times after closure. Activity is expressed as a percentage of the total activity at closure. To illustrate how activity declines in a longer time perspective, the figure contains two graphs with different activity scales.*

The nuclides that make the greatest contributions to the total activity are shown in Figure 1-5. The radionuclide Ni-63 dominates from the start, but after about 1,000 years the activity consists mainly of Ni-59 together with inorganic and organic C-14. The nuclides that have the highest activity are not necessarily those that contribute most to the radiotoxicity of the waste. The radiotoxicity of different nuclides is dependent on the type and energy of the radiation they emit.

For example, the radiation from I-129 has a much higher energy than that from Ni-59. By radiotoxicity is meant in the figures dose via oral intake (ingestion). Radiotoxicity as a function of time has been calculated as a percentage of the total radiotoxicity of the waste at closure in 2040. Calculations of radiotoxicity are presented in Appendix C. Figure 1-6 shows the relative radiotoxicity over time and the nuclides that contribute most to the radiotoxicity of the waste.

Over short spans of time, 0–100 years, short-lived nuclides (physical half-life < 30 years) such as Cs-137 dominate the radiotoxicity, but as they decay the radiotoxicity will be dominated by more long-lived radionuclides. After 1,000 years Am-241, inorganic and organic C-14, Pu-239 and Ni-59 contribute most to radiotoxicity.

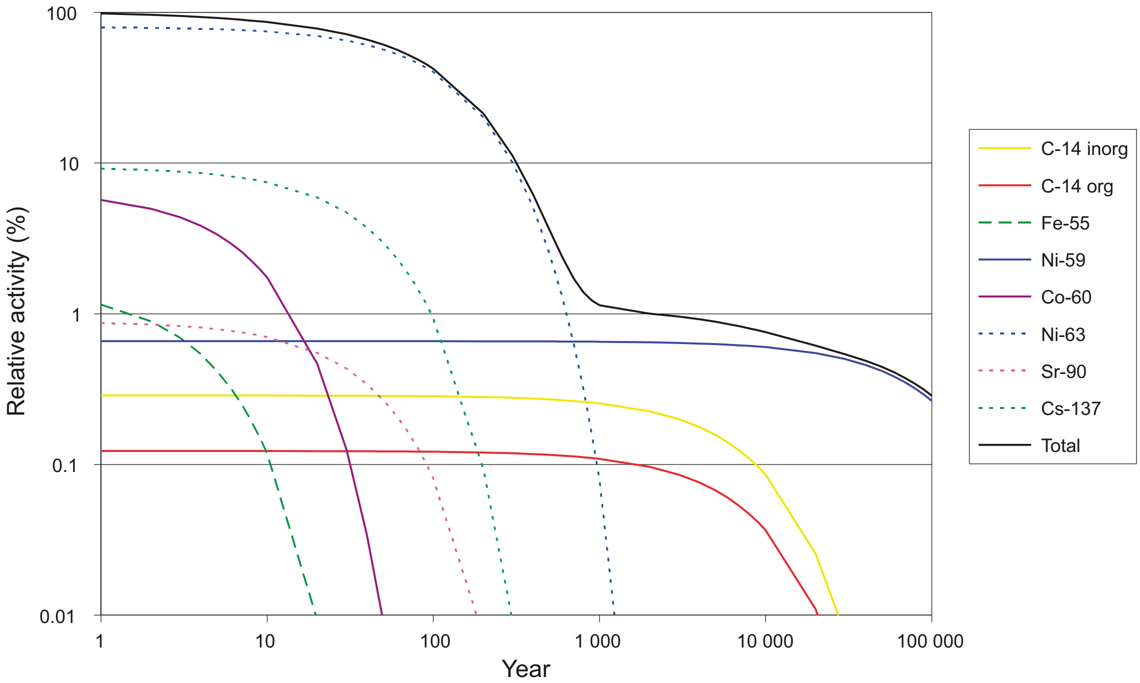


***Figure 1-5.** Percentage contributions to the total activity by dominant radionuclides as a function of time.*

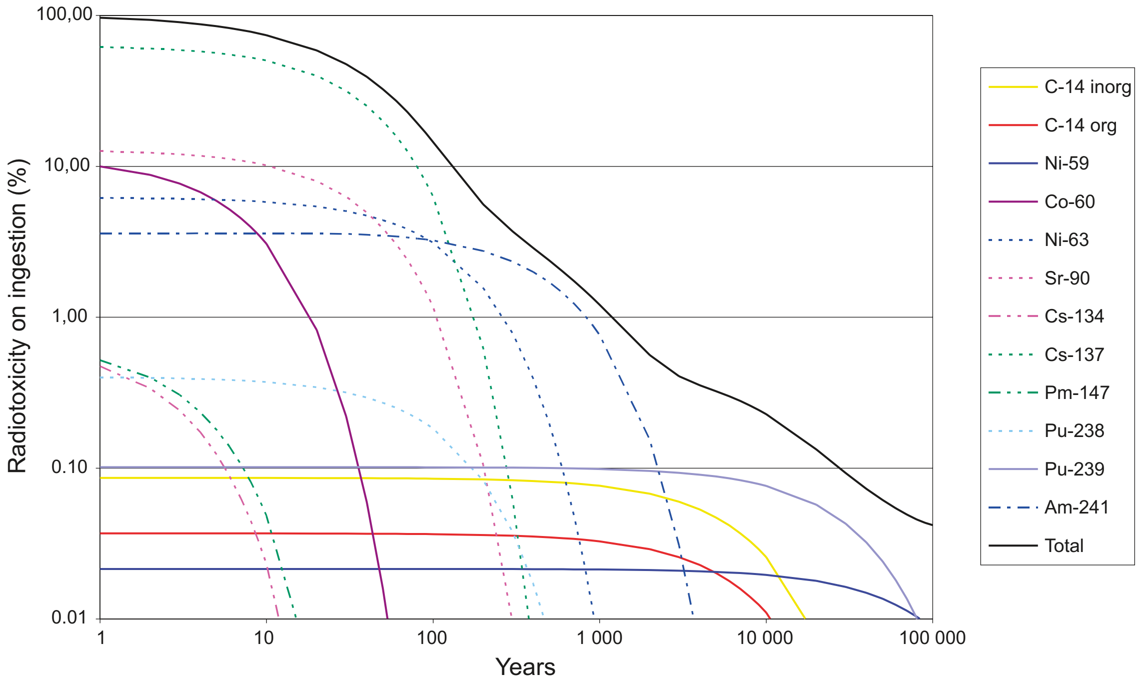


***Figure 1-6.** Percentage contributions to the total radiotoxicity from the radionuclides that contribute most to radiotoxicity as a function of time.*

There are three types of rock vaults and one silo in SFR 1, intended for waste with different activity contents. Most of the activity is placed in the silo, which has the most elaborate engineered barriers. Only low-level waste is placed in BLA, which has no engineered barriers. The radiotoxicity of the waste is illustrated in Figure 1-7.

The fact that the relative radiotoxicity of the waste declines with time is shown by Figures 1-6 and 1-7, but the figures say nothing about how toxic the waste in SFR 1 is in absolute terms. Figure 1-8 shows the radiotoxicity of the waste in SFR 1 compared with the radiotoxicity of the naturally occurring radionuclides in the rock mass that corresponds to the excavated volume of rock in SFR 1. The natural uranium content of the rock has been set at 4 ppm in the calculations. The uranium content is based on airborne surveys over the area undertaken by SGU (Geological Survey of Sweden).

/SGU 2008/. It has also been assumed that radiometric equilibrium prevails in the rock mass, i.e. that daughter nuclides of uranium are present in the natural concentrations that result when the uranium has been present for a long time in the bedrock. For the waste in the repository, the chain decay of U-238 has been taken into account, see Figure 1-7 where the relative radiotoxicity of U-238 and its daughter nuclides increases with time for BLA. The calculations are presented in Appendix C.

After about 300 years, the radiotoxicity of the waste is equivalent to that of the excavated rock in SFR 1, see Figure 1-8.

Also important for the repository's long-term safety is the mobility of the radionuclides, which affect the transport of the nuclides from the repository to the biosphere. A nuclide with high radiotoxicity whose transport is effectively retarded by sorption in the repository and the surrounding rock may in reality contribute less to the long-term consequences of the repository than a mobile nuclide with lower radiotoxicity.

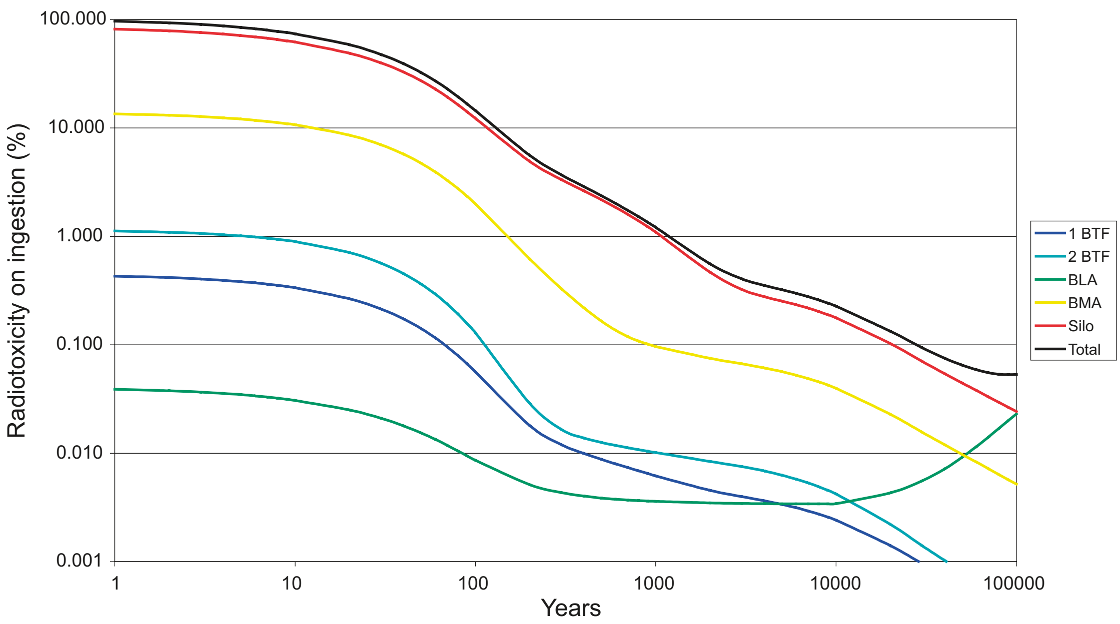


Figure 1-7. *Percentage contributions to the total radiotoxicity from the different repository parts in SFR 1. The contribution from BLA increases with time due to the creation of daughter products from the decay chain of U-238.*

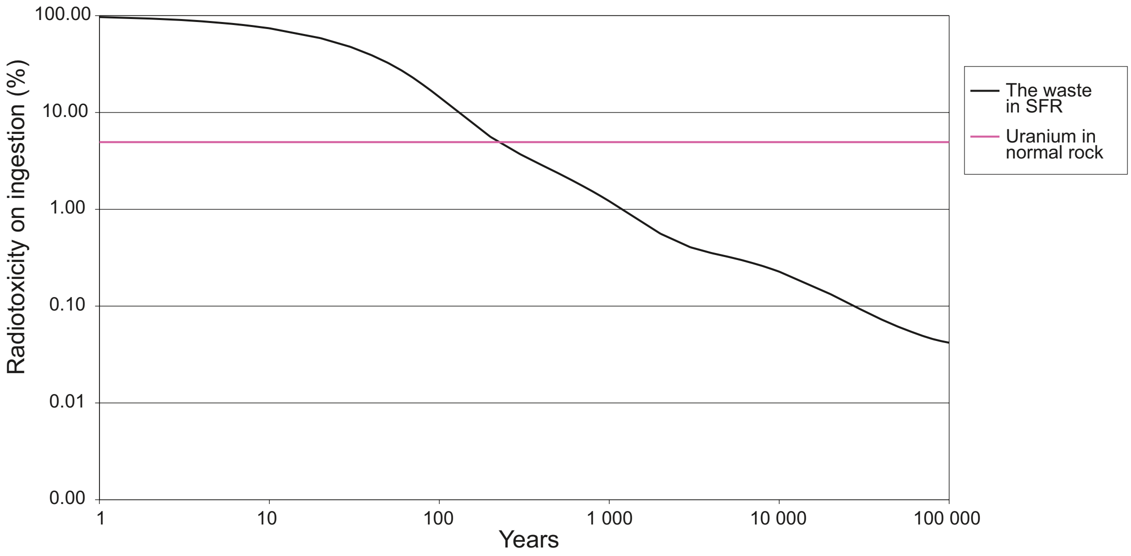


Figure 1-8. *The radiotoxicity of the waste compared with the radiotoxicity of normal rock.*

1.2.3 Regulatory requirements on assessment and safety

The format and scope of a safety assessment, and in particular the criteria to be used to judge the safety of the repository, are stipulated in regulations from SKI and SSI. The regulations are based on three framework laws: the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act. National legislation, and here Sweden's is no exception, is influenced by international rules recommendations.

When it comes to the long-term safety of a final repository for nuclear waste, there are two regulations of particular importance, issued by SSI and SKI:

- "SSI's Regulations on the Protection of Human Health and the Environment in connection with the Final Management [disposal] of Spent Nuclear Fuel and Nuclear Waste" (SSI FS 1998:1) and guidelines of the application of these regulations (SSI 2005:5).
- "SKI's Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste" (SKIFS 2002:1). General recommendations concerning the application of the regulations are contained in the same document.

Essential portions of these three documents are reproduced in Appendix A. The appendix also indicates how the requirements in the regulations are handled in the safety analysis report by references to relevant sections or by a description. In this way SKB wishes to show how the regulatory requirements are met in the safety assessment.

Final disposal of spent nuclear fuel, SSI 1998:1

The portions of SSI FS 1998:1 most relevant to the assessment of long-term safety state the following:

- Protection of human health shall be ensured by fulfilment of a risk criterion stipulating that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". By "harmful effects" is meant cancer and hereditary defects. According to SSI, this risk limit is equivalent to a dose limit of about $1.4 \cdot 10^{-5}$ Sv/year, which is about one percent of the natural the background radiation in Sweden.
- As far as environmental protection is concerned, biological effects of ionizing radiation due to releases of radioactive material from a repository to important habitats and ecosystems shall be described based on available knowledge.

- The consequences of intrusion into a repository shall be reported and the protective capability of the repository after intrusion shall be described.
- SSI requires a more detailed assessment for the first 1,000 years after closure of the final repository than for subsequent periods.

SSI has also issued guidelines with respect to application of SSI FS 1998:1 (SSI 2005:5). One guideline regarding the criterion for individual risk is that:

- If the exposed group only consists of a few individuals, the criterion of the regulations for individual risk can be considered to be complied with if the highest calculated individual risk does not exceed 10^{-5} per year.

Safety in connection with the disposal of nuclear waste, SKIFS 2002:1

The most relevant portions in SKIFS 2002:1 for the assessment of long-term safety state the following:

- The safety assessments shall comprise features, events and processes which can lead to the dispersion of radioactive substances after closure.
- A safety assessment shall comprise as long a time span as barrier functions are required, but at least ten thousand years.
- Reporting of the following is required:
  - methods for system description and system development,
  - methods for selection of scenarios, including a main scenario the that takes into account the most probable changes in the repository and its environment,
  - the applicability of models, parameter values and other premises used in the analyses,
  - management of uncertainties and sensitivity analyses.
- with respect to the analysis of post-closure conditions, a description is required of the evolution in the biosphere, the geosphere and the repository for the selected scenarios.

SKIFS 2002:1 also contains guidelines ("general recommendations") concerning the application of the regulations. These recommendations include more detailed information on, for example, classification of scenarios and uncertainties.

1.2.4 Review comments concerning 2001 safety assessment

The views of the regulatory authorities concerning the preceeding safety report /SKB 2001a/ and the requirements on supplementary information from SKB are presented in SKI's and SSI's review /SSI/SKI 2003/ of the 2001 safety report.

The regulatory authorities requested the following supplementary information, see Appendix B for all requirements made in decisions from SKI and SSI:

- An account of requirements made on barriers and barrier functions at different points in time and how they comprise, together with the scenarios, a basis for the justification of consequence analyses performed.
- An account of the uncertainties in the nuclide inventory, above all for the difficult-to-measure nuclides C-14, Ni-59, Ni-63 and I-129.
- An account of the importance of long-term climate changes and the repository's protective capacity for times beyond 10,000 years after closure.
- An assessment of the long-term degradation of the concrete and bentonite barriers.
- An account of uncertainty and sensitivity analyses of dose and risk with respect to the uncertainty of input data, including groundwater flows, sorption data, biosphere evolution, radionuclide content, etc.

1.2.5 Priority areas for in-depth analysis for 2008 safety analysis report

The present safety analysis report is based on a complete safety assessment and thereby supersedes the previous safety assessments, including the safety report from 2001 /SKB 2001a/. Important improvements introduced in this safety analysis report are:

- Safety functions and preliminary safety performance indicators for SFR 1 have been defined and applied in the scenario analysis, see Chapter 5.
- New correlation factors have been determined for C-14, Ni-59, Ni-63, I-129, Cl-36, Tc-99, Mo-93 and Cs-135. Furthermore, uncertainties in the inventory have been estimated /Almkvist and Gordon 2007/.
- Degradation of the concrete and bentonite barriers has been studied for times up to 100,000 years after closure /Cronstrand 2007, Emborg et al. 2007/.
- A generic hydrogeology model has been constructed for times between 10,000 and 100,000 years /Vidstrand et al. 2007/.
- A probabilistic approach is applied in the model for migration calculations. Parameters dealt with probabilistically include length of flow paths and sorption data /Thomson et al. 2008a/.

1.3 Report structure

The report on long-term safety comprises eleven chapters. Following is a brief description of the chapters. In order to be able to assimilate all the information in SAR-08, General Part 2, "Long-term safety", a general knowledge of the layout, installations and principles of operation of the SFR 1 may be helpful. See Chapters 5 and 6 of the safety analysis report in General Part 1, "Facility design and operation".

Chapter 1 – Introduction. The chapter describes the purpose, background, format and contents of SAR-08, applicable regulations and injunctions, and the regulatory authorities' previous review comments. Furthermore, definitions are given of terms and abbreviations used in SAR-08, General Part 2, "Long-term safety".

Chapter 2 – Method. The chapter provides an overall description of the method used for the safety assessment and some aspects of the methodology are presented, such as time periods, safety principles, management of uncertainties, quality assurance and risk management.

Chapter 3 – Identification, ranking and handling of FEPs. The chapter systematically describes the factors to be taken into account in the assessment in the form of features, events and processes (FEPs). Interaction matrices are used to structure the information.

Chapter 4 –Initial state in the repository and its environs. The chapter describes the initial state, defined as the expected state of the repository and its environs, at closure in 2040. The description of the initial state is based on the technical design of the repository, present-day knowledge concerning conditions in the repository and its environs, and the expected evolution of the repository up until 2040.

Chapter 5 – Safety functions and safety performance indicators. Safety functions and safety performance indicators are identified and described in this chapter. A safety function is a role by means of which a repository component contributes to safety.

Chapter 6 – Reference evolution for the repository and its environs. This chapter describes the reference evolution of the repository and its environs and how the safety functions of the repository can be affected by this evolution up until 100,000 years after closure.

Chapter 7 – Selection of scenarios. This chapter describes how scenarios are selected based on safety performance indicators and interaction matrices. The selected scenarios illustrate the most important processes leading to the migration of radionuclides in the repository and to exposure of man and environment. The description of the processes is based on the evolution of the repository's properties, its environs and the biosphere.

Chapter 8 – Description of calculation cases. This chapter describes the calculation cases that are used to illustrate the radiological consequences of the scenarios that have been judged to be of importance in the scenario analysis.

Chapter 9 – Radionuclide transport and dose calculations. The results of radionuclide transport and dose calculations are reported in this chapter.

Chapter 10 – Assessment of risk. This chapter presents an integrated account of calculated risks and a comparison with criteria stipulated by the regulatory authorities.

Chapter 11 – Conclusions. The conclusions of the present safety assessment are presented in this chapter, and major changes made compared with previous safety assessments are summarized.

Finally, a **Reference list** and **Appendices A - D** are submitted.

1.3.1 Important background reports for long-term safety

Specific reports of central importance for the conclusions and analyses in the main report have been used in the assessment of long-term safety. The most important background reports are shown in Table 1-1.

Table 1-1. The most important background reports for judging the long-term safety of SFR 1.

Title	Reference list
Low and Intermediate Level Waste in SFR 1. Reference Waste Inventory 2007.	Almkvist L, Gordon A, 2007
Models used in the SFR 1 SAR-08 and KBS-3H safety assessments for calculation of C-14 doses.	Avila R, Proehl G, 2008
Dose assessments for SFR 1.	Bergström U, Avila R, Ekström P-A, de la Cruz I, 2008
Modelling the long-term stability of the engineered barriers of SFR with respect to climate changes.	Cronstrand P, 2007
Långtidsstabilitet till följd av frysning och tining av betong och bentonit vid förvaring av låg- och medelaktivt kärnavfall i SFR 1.	Emborg M, Jonasson J-E, Knutsson S, 2007
Project SAFE Complexing agents in SFR.	Fanger G, Skagius K, Wiborgh M, 2001
Modelling the geochemical evolution of the multi-barrier system of the Silo of the SFR repository. Final report.	Gaucher E, Tournassat C, Nowak C, 2005
Update of priority of FEPs from Project SAFE.	Gordon A, Lindgren M, Löfgren M, 2008
Modelling of Future Hydrogeological Conditions at SFR, Forsmark.	Holmén J G, Stigsson M, 2001a
Details of predicted flow in deposition tunnels at SFR, Forsmark.	Holmén J G, Stigsson M, 2001b
SFR inverse modelling. Part 2. Uncertainty factors of predicted flow in storage tunnels and uncertainty in distribution of flow path from storage tunnels.	Holmén J, 2007
Modelling of long-term concrete degradation processes in the Swedish SFR repository.	Höglund L O, 2001
Description of surface systems. Preliminary site description Forsmark area – version 1.2.	Lindborg, T editor, 2005
Microbial features, events and processes in the Swedish final repository for low- and intermediate-level radioactive waste.	Pedersen K, 2001
Characterisation of bituminised waste in SFR 1.	Pettersson M, Elert M, 2001
Project SAFE Scenario and system analysis.	SKB, 2001b
Project SAFE Compilation of data for radionuclide transport analysis.	SKB, 2001c
The biosphere at Forsmark.	SKB, 2006b
Model summary report for the safety assessment SFR 1 SAR-08.	SKB, 2008
Radionuclide release calculations for SFR 1 SAR-08.	Thomson G, Miller A, Smith G, 2008a
Hydrogeological flux scenarios at Forsmark – Generic numerical flow simulations and compilation of climatic information for use in the safety analysis SFR 1 SAR-08.	Vidstrand P, Näslund J-O, Hartikainen J, Svensson U, 2007

1.4 Terms and abbreviations

Following are definitions of terms and abbreviations that occur in the running text in SAR-08, General Part 2, "Long-term safety". The terms coincide with the terminology used in applicable legislation and regulations. Designations used in the text that are not conventional are also explained.

Barrier	Physical confinement of radioactive substances (SKIFS 2004:1). The purpose of the barrier is to confine the facility's content of radioactive substances. If one barrier is breached, the next should take over.
Becquerel (Bq)	The special name of the unit of radioactivity. One becquerel is equal to one disintegration per second.
Rock vaults	"Rock vaults" generally refers to BMA, BLA and BTF (BTF 1 and 2).
BLA	Rock vault for low-level waste
BMA	Rock vault for intermediate-level waste
BTF	Rock vault for concrete tanks
BWR	Boiling Water Reactor
Detrivores	Decomposers such as fungi and bacteria.
Operational waste	Waste from the operation of nuclear reactors and Clab, and radioactive waste from Studsvik.
Effective dose	The sum of all equivalent doses to organs or tissues, weighted for their different sensitivity to radiation (SSI FS 1998:4).
Equivalent dose	An absorbed dose to an organ or tissue, weighted by factors that take into account the biological effect of the particular type of radiation (SSI FS 1998:4).
External exposure	Irradiation from a radiation source situated outside the body (SSI FS 1998:4).
Closure	Sealing of a repository opening after it has been filled with waste or when no additional waste will be deposited
Post-closure phase	The phase that begins when SFR has been totally closed and sealed.
Disposal chamber	An opening in the final repository in which waste is emplaced for final disposal.
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
Internal exposure	Irradiation from radioactive substances after intake into the body via the respiratory passages or the gastrointestinal tract or through the skin (SSI FS 1998:4).
Collective dose	The sum of the effective dose equivalent for all individuals in a given region or belonging to a given region or belonging to a given population group or vocational group or performing a certain type of work (SSI FS 2000:10).
Critical group	A group of individuals who are exposed to relatively uniform irradiation from a source that can be regarded as being representative of the irradiation to which the most exposed individuals in the population are exposed (SSI FS 2000:12).
Low-level waste	Waste from, for example, nuclear facilities and hospitals. Includes protective clothing, tools, filters and other items that may have been contaminated with radioactivity.
Intermediate-level waste	Consists primarily of process waste from the nuclear power industry, such as ion exchange resins. The waste may contain rather high concentrations of short-lived radionuclides and must therefore be radiation-shielded during handling. It also sometimes contains small quantities of long-lived radionuclides.
Periglacial	Physical land processes that occur in the cold climate immediately outside glaciers and ice sheets. The cold climate creates permafrost, permanently frozen ground.
SI	Site Investigation
PWR	Pressurized Water Reactor
Radioactivity	The property of a substance whereby it emits ionizing radiation.
	Radioactivity is a property, not a physically measurable quantity. It can be of different types: alpha, beta, gamma or neutron radiation.
SAR	Safety Analysis Report

Seismic class	Entails a classification of buildings, systems and subsystems based on the extent to which they must function during and after a design earthquake.
SFR	Final repository for reactor waste.
SFR 1	Final repository for radioactive operational waste
Sievert (Sv)	The unit that is used to indicate how harmful (toxic) radiation is. Radiation doses are normally given in thousandths of a sievert, millisieverts (mSv).
Silo	Disposal chamber (concrete cylinder) in SFR 1 intended for the operational waste that has the highest activity content.
Silo repository	Includes the silo and the bentonite around the silo.
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co)
SKI	Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate)
SKIFS	The Swedish Nuclear Power Inspectorate’s Regulatory Code
Final repository	A repository for the final disposal of radioactive waste which can, after the waste has been deposited, be closed and then abandoned without requiring any additional measures.
SSI	Statens strålskyddsinstitut (Swedish Radiation Protection Authority)
SSI FS	Swedish Radiation Protection Authority’s Regulatory Code
Standard	Guideline published by a national or international body governing product design or testing. Conformance is voluntary.
Total closure	The closure (sealing) of the entire repository that occurs when all waste has been deposited. After total closure the repository is supposed to act as a passive system and no human interventions should be necessary to guarantee long-term function.

2 Method

2.1 Introduction

This chapter provides an overview of the method that has been used for the safety assessment of SFR. The method is based in part on the method that was used for SR-Can and is described in SR-Can's Main Report /SKB 2006a/.

The main purpose of this safety assessment for SFR 1 is to show whether the final repository can be considered to be radiologically safe in the long term. This is done by comparing estimates of radiation doses from calculated releases of radionuclides from the repository with regulatory criteria. In a long-term perspective, the primary safety function of SFR 1 is to retard the migration of nuclides from the waste. This gives most radionuclides time to decay before they risk reaching the biosphere. An important purpose of the present safety assessment is to show that this retardation is sufficient to ensure safety under many different conditions for a long time.

It is important to be able to support all claims and assumptions in the assessment with scientific and technical arguments in order to lend credibility to the calculated results. Demonstrating understanding of the final repository system and its evolution is an important part of every safety assessment.

The repository system – broadly defined as the deposited nuclear waste, the waste containers, the engineered barriers, the host rock and the biosphere surrounding the repository – will change with time. The future state of the system will depend on the following:

- the initial state of the system,
- a number of thermal, hydraulic, mechanical and chemical processes that act internally in the repository system over time (internal processes),
- outside forces acting on the system (external processes).

Internal processes include, for example, groundwater movements and chemical processes that affect engineered barriers. Another example is production of gas as a result of oxidation of metals. If gas production takes place in the silo, there is a possibility that the gas pressure could force radioactive water out into the silo's concrete wall. External processes include future climate and climate-related processes, for example glaciation and land uplift, or the current process of global warming. Future human interventions could also affect the repository.

An AMF (Assessment Model Flowchart) has been used to schematically represent the models and data that are used to quantify the processes that occur in and around the repository (internal, external and geosphere) and how they are interlinked, see Figure 2-1. In addition to the models presented in the flowchart, smaller calculations have been carried out such as pretreatment of input data and post-calculations for results. These processes and calculations are not visible in the AMF.

The initial state, the internal and external processes and the ways in which these factors together determine the evolution of the repository can never be fully described or understood. Uncertainties of various kinds are therefore associated with all aspects of the repository's evolution and thereby with the safety assessment. How these uncertainties are managed is therefore of central importance in all safety assessments.

The next section provides a brief overview of the analysis method.

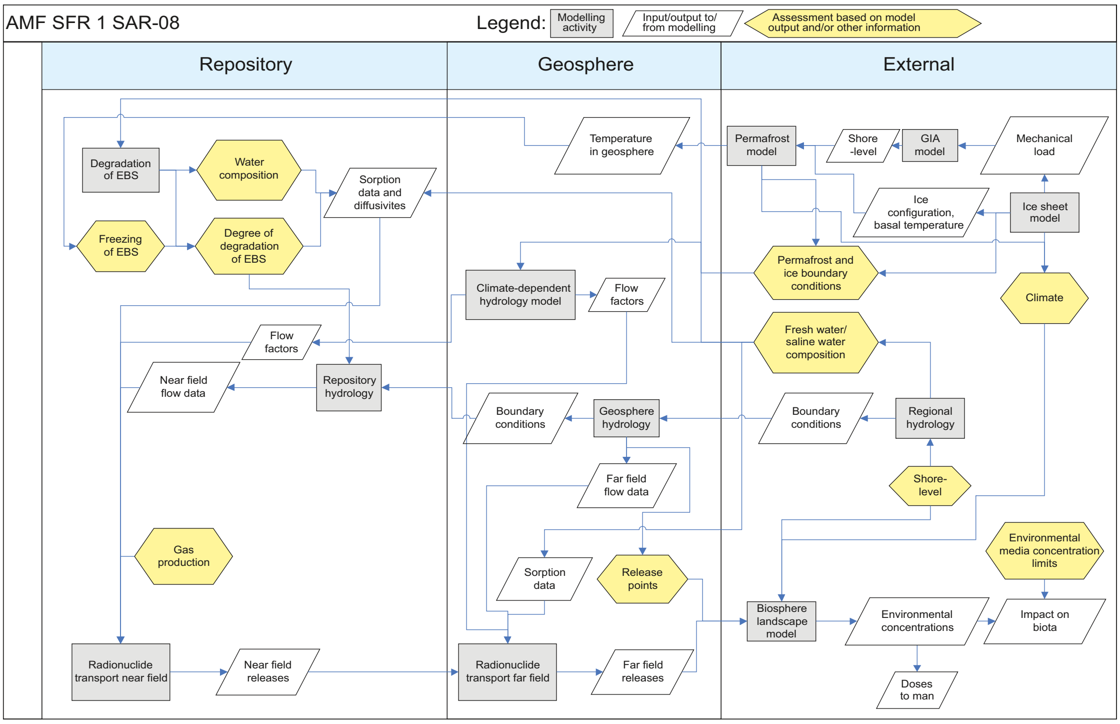


Figure 2-1. AMF (Assessment Model Flowchart): schematic representation of how models and data are used for SFR 1 in SAR-08. GIA, Glacial Isostatic Adjustment, gives land subsidence and uplift as a result of the advance or retreat of an ice sheet.

2.2 Steps in the method

A nine-step method based on the method developed for SR-Can has been used. It is summarized in Figure 2-2. The nine steps are described in greater detail in the following sections.

2.2.1 FEP processing

The initial step in a safety assessment is to identify all the factors that are important for the evolution of the repository and that should be studied in order to gain a good understanding of the evolution and safety of the repository. This is done in a screening of all features, events and processes (FEPs) that are of importance for the evolution of the repository. This screening has been conducted in two steps. The first step was taken in the SAFE project in 2001 and covers the period up until 12,000 AD /SKB 2001b/. The second step involves a screening of FEPs to take into account the extended time perspective comprised by this analysis, in other words times up to around 100,000 years after closure /Gordon et al. 2008/.

An FEP analysis in the SAFE project was arrived at via a series of expert group meetings in accordance with a method based on interaction matrices. This method comprises a systematic identification of processes and interactions between processes that act in the system and documented expert assessments of the importance of these processes and interactions for the evolution of the system. Three coupled matrices were used to describe the repository system in SFR 1: one for the repository itself, one for the geosphere and one for the biosphere. The content of the matrices was checked against international lists of FEPs in order to ensure as far as possible that all relevant FEPs have been included.

In the second and supplementary FEP analysis, the prioritization of the interactions according to importance done in the first analysis was re-evaluated based on the longer time perspective. In addition, a cross-check was carried out against new regulations from the regulatory authorities (SKIFS 2002:1 and SSI FS 2005:5), the regulatory review of the SAFE project, and the FEPs arrived at by SKI for SFR 1 /Miller et al. 2002/.

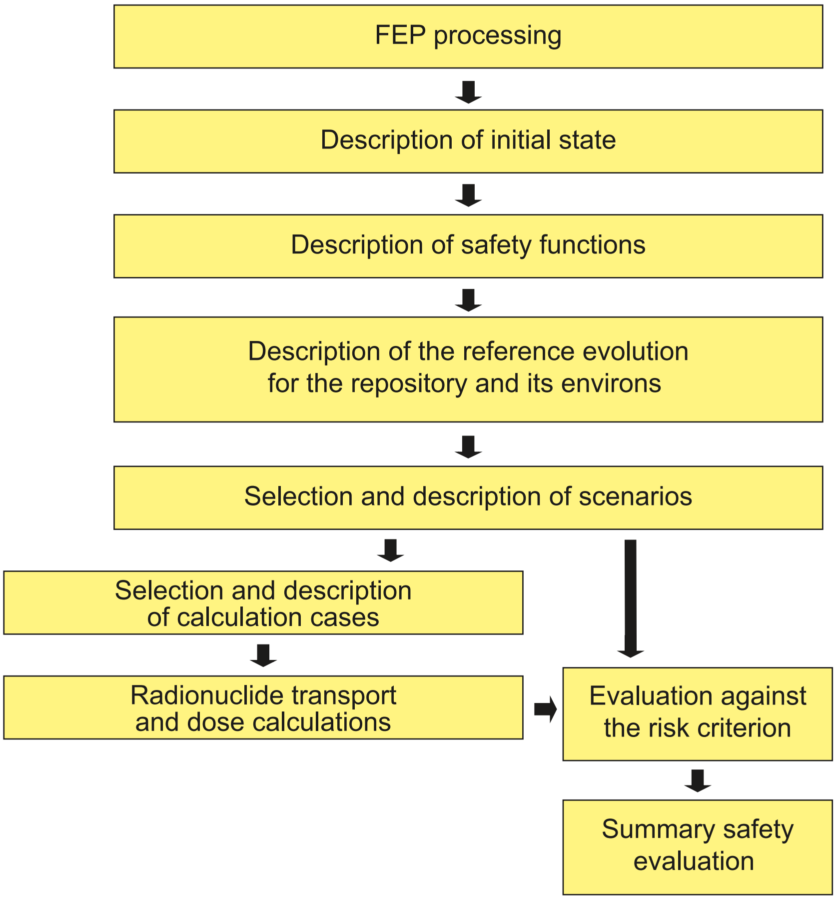


Figure 2-2. *Overview of the nine steps in the method used in the present safety assessment.*

The handling of the features, events and processes (FEPs) that must be studied provides a good understanding of the evolution of the repository, and the material that is gathered is used in both the description of the reference evolution and scenario selection (see below).

The FEP analysis and its results are described in greater detail in Chapter 3.

2.2.2 Description of initial state

The initial state of the system is described based on the state of the repository, the rock and the biosphere at the time of closure, in the year 2040, and comprises the point of departure for the further analyses. The description of the initial state is based on the technical design of the repository and present-day knowledge of conditions in the repository and its environs. The initial state is described in greater detail in Chapter 4.

2.2.3 Safety functions

This step consists of identifying and describing the system's safety functions and how they can be evaluated with the aid of a set of safety performance indicators that in principle consist of measurable or calculable properties of engineered barriers, geosphere and biosphere.

A safety function is a property by means of which a repository component, such as a barrier, contributes to the long-term safety of SFR 1. There are two overall safety principles for SFR 1 – limited quantity of radioactivity in the waste and retardation of radionuclide transport.

The overall safety principles have been broken down and described as a number of specified safety functions in Chapter 5. An example is engineered barriers, which contribute to restricting the water flow through the waste and thereby the transport of solutes from the repository. The corresponding safety function is then the ability to restrict advective transport.

A safety performance indicator is a measurable or calculable quantity by means of which a safety function can be evaluated. In the example with engineered barriers and their ability to restrict advective transport, hydraulic conductivity is a suitable quantity for determining whether this safety function is maintained.

The fact that a safety function cannot be fully maintained does not necessarily mean that the safety of the repository is jeopardized, but rather that more in-depth analyses and data are needed to evaluate safety. On the other hand, the safety of the repository is not guaranteed even if all safety functions are maintained. Quantitative calculations are required to ensure, for example, that SSI's risk criterion (see section 1.2.3) is fulfilled.

Safety functions and indicators are tools for analyzing the future performance of a repository and for arriving at an extensive set of scenarios. But all scenarios do not necessarily have to undergo extensive analysis with transport and dose calculations.

Safety functions and safety performance indicators for SFR 1 have been identified at expert group meetings and are described in greater detail in Chapter 5.

2.2.4 Description of reference evolution

When all features, events and processes of importance for the evolution of the repository have been identified, they are studied. The results of these studies have been documented in a series of background reports. Based on the overall picture provided by the information in these background reports, a reference evolution is described for the repository. The reference evolution is a reasonable example of the repository's future evolution, and the relevant time horizon is 100,000 years.

The description of the reference evolution has been divided into three time periods:

- The first 1,000 years after closure, i.e. the period up until 3,000 AD.
- The period from 3,000 AD to 20,000 AD.
- The period from 20,000 AD until around 100,000 AD.

For each period, a description is given of the evolution of the repository and its environs and the safety functions are evaluated. In order to structure the descriptions of the evolution in the repository, they have been divided into four categories: thermal, mechanical, hydrogeological and chemical (TMHC).

The reference evolution is described in Chapter 6.

2.2.5 Selection and description of scenarios

A set of scenarios is defined, described and analyzed. Uncertainties in the future evolution of the repository as it is described in the reference evolution are managed by also studying alternative repository evolutions in accordance with SKI's regulations SKIFS 2002:1. The basis for this analysis is the repository's reference evolution as it is described in Chapter 6, which constitutes the main scenario. Less probable scenarios and residual scenarios are then defined for different repository evolutions as well as for the event, process or data uncertainties that initiate the alternative repository evolution.

A set of scenarios is based on the safety functions defined in Chapter 5. Each function corresponds to an alternative repository evolution, and possible courses of events that could lead to loss of the function are studied. This is done by studying, based on the FEP analysis described in Chapter 3, what factors could cause a loss of the function in question. The purpose is to find evolutions that are less favourable for the function than that described in the main scenario. Firstly, the possibility that there are additional uncertainties that were not addressed in the reference evolution is examined for the phenomena that were studied in that evolution, and secondly, the question of whether there are relevant phenomena for the function that were not included in the reference evolution is studied.

If the possibility of such a scenario occurring cannot be ruled out, it is classified as a less probable scenario and an attempt is made to estimate its probability. If no reasonable causes of a scenario can be identified, it is classified as a residual scenario.

The radiological consequences of each scenario are then quantified by radionuclide transport calculations, described in Chapter 8.

The main scenario and the less probable scenarios are included in the summation of risk for the repository.

In accordance with the regulatory requirements, a set of scenarios where human intrusion is studied is also selected. Also according to the regulations and general recommendations, no probability estimates are made for these scenarios and they are not included in the summation of risk for the repository. In addition, a number of hypothetical scenarios intended to shed light on the importance of barriers and barrier functions are selected, in accordance with the regulations. These hypothetical cases are not included in the summation of risk either.

Chapter 7 describes selection and analysis of scenarios and identification of possible combinations of scenarios.

2.2.6 Selection and description of calculation cases

To judge the consequences of the scenarios that are relevant according to the preceding section, they have to be described with the aid of calculation cases and analyzed with the aid of mathematical models.

The calculation cases have been divided into three groups corresponding to the three scenario groups: main scenario, less probable scenarios and residual scenarios.

The calculation cases are described in Chapter 8.

2.2.7 Radionuclide transport and dose calculations

This step comprises the quantitative calculation of radionuclide transport from the repository (the near field) through the rock (the geosphere) to the biosphere and the dose which man can obtain from exposure to radionuclides.

Calculation models are also selected in this step (one for the repository, one for the geosphere and one for the biosphere), along with input data for the calculations. An uncertainty assessment is performed for certain input data that have been found in previous safety assessments to be of essential importance for the results (see also section 2.5.4). This uncertainty assessment provides a parameter interval that is used for probabilistic calculations. Uncertainty and sensitivity analyses are carried out for both the radionuclide transport and the dose calculations, and these are presented in background reports /Thomson et al. 2008a, Bergström et al. 2008/.

Radionuclide transport and dose calculations are presented in Chapter 9.

2.2.8 Evaluation against the risk criterion

The risk is calculated in this step by multiplying the probability of the scenarios by the calculated dose consequence. The calculated risk is compared with SSI's risk criterion. See further Chapter 10.

2.2.9 Summary safety evaluation

The assessment of the long-term safety of SFR 1 is based on an integrated evaluation of both quantitative and qualitative results. Calculated doses and risk estimates are compared with criteria stipulated in SSI's regulations. The long-term protective capability of the different barriers is discussed on the basis of results of the analysis of repository evolution. The reliability of different analyses and assessments is discussed and evaluated, see further Chapter 11.

2.3 Time periods

By far most of the waste in SFR 1 is short-lived. As a result of radioactive decay, only about 2 percent of the activity remains 1,000 years after closure and only about 0.3 percent after 100,000 years, see section 1.2.2. Even though most of the activity decays during a relatively short period, the safety assessment needs to cover a long enough period to enable future harmful effects on man and the environment to be assessed. The question of how far into the future the safety assessment should extend is addressed in regulations from SKI and SSI.

2.3.1 Requirements and recommendations from Swedish regulatory authorities

SKI's regulations SKI FS 2002:1 state that the safety assessment "shall comprise as long time as barrier functions are required, but at least ten thousand years" after closure. The general recommendations concerning the regulations state that the time scale for an assessment should be considered in relation to the hazard posed by the repository's radioactive contents, in comparison with naturally occurring radionuclides.

SSI's regulations SSI FS 1998:1 state that:

- For the first thousand years following closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the impact on human health and environment.
- For the period after the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the evolution of the repository's properties, its environment and the biosphere.

The guidelines on SSI FS 1998:1 (i.e. SSI FS 2005:5) state the following:

1. "*For a repository for spent nuclear fuel or other long-lived nuclear waste, the risk analysis should cover at least approximately one hundred thousand years or the period for a glacial cycle to shed light on reasonably predictable external stresses on the repository. The risk analysis should thereafter be extended in time as long as it provides important information about the possibility of improving the protective capability of the repository, but no longer than for a time span of up to one million years.*
2. *For other repositories for nuclear waste than those referred to in point 1, the risk analysis should cover at least the time until the expected maximum consequences regarding risk and environmental impact have occurred, but no longer than a time span of up to one hundred thousand years.*"

SFR 1 constitutes a repository of the type referred to in point 2.

According to SSI the future harmful effects should not be judged to be less important than the harmful effects to which man or the environment is subjected today. However, SSI emphasizes that the initial thousand years of the repository's evolution are the most important to examine, since the toxicity of the waste is greatest then. The greatest demands are made on the safety assessment for this time period.

The situation after the initial thousand years must also be studied, and SSI stresses the importance of determining the different types of uncertainties in the background material that serves as a basis for the analyses of different eras.

In addition to the requirements made by SKI and SSI in their regulations, requirements are also stipulated in the review comments from previous safety analysis reports and decisions. One of these requirements directly concerns the time scale used in the safety assessment. This requirement says that an account must be given of the importance of long-term climate changes and the protective capability of the repository for times beyond 10,000 years after closure /SSI 2006/.

2.3.2 Time periods in the safety assessment

Besides satisfying the regulations' requirements regarding what time period should be covered by the safety assessment, an understanding can be obtained of how the radiotoxicity of the waste changes with time. The radiotoxicity of the waste decreases as its radioactivity declines. Figure 1-8 shows a comparison between the radiotoxicity of the waste in SFR 1 and that of the excavated volume of rock in SFR 1. The rock is assumed to have a natural uranium content of 4 ppm, which is a normal uranium concentration in the area around Forsmark. The comparison shows that the radiotoxicity of the waste after about 300 years is equivalent to that of the rock at SFR 1.

The regulatory authorities require that the assessment cover time spans that encompass long-term climate changes. In the reference evolution, the repository is judged to undergo both periods with permafrost and a period with an ice sheet 70,000 years after repository closure. In another possible climate evolution, the greenhouse variant, a temperate climate is assumed to prevail for 50,000 years before the relatively mild onset of the reference evolution's glacial cycle. This delay means that it will take around 100,000 years before the repository has undergone periods with both permafrost and glaciation.

A criterion that can be considered to justify a time scale for a safety assessment is that the analyzed period should extend beyond the point in time when the doses from the repository have reached a maximum. From the 2001 safety assessment, where a time scale of 10,000 years after closure was considered, it is difficult to determine with certainty whether the time of the dose maximum has been passed for certain calculation cases. This warrants the choice of a longer analysis period.

Based on the above argument, an analysis period of 100,000 years has been chosen.

2.4 Safety principles

2.4.1 Overall goals and requirements

SFR 1 must meet society's requirements on safety and a good environment as they are expressed in laws and regulations. It must also meet the owners' requirements on safety and efficiency.

Some important safety and radiation protection principles underlying the design and operation of SFR 1 are:

- The multiple barrier principle: safety should be based on multiple safety functions provided by multiple barriers. These barriers must be passive.
- In-depth defence: safety and safety awareness should permeate both the design of the barriers and the procedures intended to limit radiation doses and prevent accidents.
- Humans, animals and the environment should be protected from the harmful effects of ionizing radiation, and future generations and environments may not be exposed to greater radiation doses and/or risks than are acceptable today.

- A balance should be struck between radiation protection during operation and long-term (post-closure) safety.
- Good and reliable technology should be used in order to limit uncertainties and optimize radiation protection.
- The facility should have physical protection that hinders intrusion by unauthorized persons during the operating period.
- The facility must be able to receive visitors.
- Furthermore, the facility should be designed with a view to the environment and the safety of the users and nearby residents.

2.4.2 Post-closure safety principles

There are two main safety principles for SFR 1:
- limited quantity of radioactivity in the waste,
- retardation.

The safety principles are maintained by the following barriers: rock, waste package, engineered barriers in disposal chambers, and closure with plugs. Furthermore, the properties of the waste itself and its emplacement in the different disposal chambers contribute to the safety functions.

Isolation from man and the environment is ensured by the rock and the repository depth, and after closure also by the backfill and plugs. Locating the repository beneath the sea floor contributes to keeping the waste isolated from man for a long time to come.

The safety principles have been broken down into safety functions and are further discussed in Chapter 5.

2.5 Uncertainty management

Confidence in the results of the calculation models is important, since the assessment of the radiological consequences of the repository is based on these results. The data underlying a safety assessment are always associated with deficiencies of various kinds. To put it simply, we are faced with the task of showing that the repository has been designed with sufficient margins to be safe in spite of the incomplete knowledge available. Confidence in the results depends on how methodically any uncertainties and deficiencies have been managed.

Deficiencies may be of a qualitative or a quantitative nature. Qualitative deficiencies concern, for example, questions regarding completeness: Have all processes that affect the evolution of the repository been identified? Have all types of external processes been covered in the selection of scenarios? Other questions are quantitative: How well can the initial state be determined? How well can different processes be described quantitatively, for example concrete degradation or groundwater flow? These questions are particularly important for the analysis of radionuclide transport, which has a direct bearing on the evaluation of the repository's safety. Calculations of radionuclide transport handle large quantities of input data, which may be associated with uncertainties to a varying degree.

Uncertainty management entails reporting the uncertainties and deficiencies associated with the data underlying the analysis and managing them in the execution of the analysis.

2.5.1 Completeness in identification of FEPs and scenario selection

It is never possible to prove that all important features, events and processes have been identified. It is instead necessary to determine whether the scope of this identification is sufficient for the needs of the safety assessment.

The work of identifying all features, events and processes has been carried out systematically in accordance with a method based on interaction matrices. This method comprises a systematic identification of processes and interactions between processes that act in the system and documented expert assessments of the importance of these processes and interactions for the evolution of the system. The content of the matrices has been checked against international lists of FEPs in order to ensure as far as possible that all relevant FEPs have been included in the matrices.

The efforts underlying the attempt to obtain an adequate description of FEPs are described in Chapter 3, in the scenario report /SKB 2001b/ and in /Gordon et al. 2008/.

Nor is it possible to guarantee a comprehensive choice of scenarios. In order to ensure as far as possible that all relevant scenarios have been identified, the safety functions identified for SFR 1 have been used. This puts the focus on safety questions in connection with the selection of scenarios. A cross-check against the handling of FEPs ensures that all relevant FEPs are included in the analyses. Last but not least, the factual review constitutes a quality assurance step.

2.5.2 Quantification of initial state

The initial state is the point of departure for model calculations of repository evolution and thereby a part of the input data required for the model calculations. The description is associated with uncertainties. This is mainly dealt with by the choice of data for the reference evolution (see section 2.5.4) and sometimes further in the analysis of different scenarios, for example by analyzing the dose consequences of an overestimated nuclide inventory.

2.5.3 Conceptual uncertainty

The term "conceptual uncertainty" refers to those uncertainties resulting from an incomplete understanding of a process as well as those uncertainties resulting from the fact that a mathematical model does not correctly describe a process (for which there may nevertheless be a good basic understanding).

The understanding of every process that has been identified comes from a large number of background reports. The understanding of every process that has been identified in the early FEP analysis is discussed briefly in the scenario report /SKB 2001b/. The aim is to describe all processes as realistically as possible. Where realistic assumptions cannot be supported due to an imperfect understanding of the impact of the process, assumptions are made so that the consequences of unfavourable processes are overestimated and conversely so that the consequences of favourable processes are neglected. For example, in BLA, where the unconditioned low-level waste is disposed of, the degradation and transformation of the waste is controlled by several complex processes and interactions. Instead of attempting to describe these processes in detail, the simplified assumption is made that the waste matrix does not contribute to any retardation of radionuclide transport.

2.5.4 Uncertainties in input data for calculations of radionuclide transport

The results of the calculations of radionuclide transport and dose are crucial for the evaluation of the repository's safety. It is then especially important to ensure the quality of these calculations.

In order to shed light on uncertainties in input data, probabilistic calculations have been carried out for hydrogeology, radionuclide transport and dose exposure.

The data that are used directly for calculations of radionuclide transport and dose have, wherever possible, been taken from the data report produced in SR-Can /SKB 2006c/, from new background reports, but also from the data report in the SAFE project /SKB 2001c/.

The sources of input data are presented in section 2.7.1. Data and uncertainties in data are discussed in the data report for the SAFE project /SKB 2001c/ and SR-Can /SKB 2006c/, while data included in the radionuclide transport calculations are discussed in the background report for transport calculations /Thomson et al. 2008a/.

Data selection conforms to the following principles:

- data selection is based primarily on the different analyses of the evolution of the repository and on the description of the initial state,
- selection of data should be justified either directly or via reference,
- if the same parameter is used in different analyses, the same data should be used. If other data are used, the reason should be explained,
- the uncertainty in the data should always be discussed and quantified, if possible,
- data with quantified uncertainties should be used if possible for probabilistic calculations. If there are no quantified uncertainties, realistic data should be used and, where warranted, conservative estimates.

2.6 Risk management

SSI has established criteria against which the results of risk calculations should be compared in order to ascertain whether the repository satisfies stipulated requirements on long-term safety. These requirements are often given as permissible risk limits for man, but also as qualitative criteria for the environment. The repository must not adversely affect biodiversity or the sustainable use of biological resources.

SSI stipulates that the annual risk of harmful effects from the repository may not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk (the most exposed group). Converted to dose using SSI's probability coefficient for harmful effect per dose unit received, 7.3 percent per Sv (SSI FS 2005:5), this gives a limit for annual dose of 14 µSv. This criterion applies if the group is relatively large. If, however, the exposed group consists of a few individuals, the annual risk for the most exposed individual can be used against a risk criterion of 10^{-5} per year, which is equivalent to an annual dose of 140 µSv. It is against these dose values – 140 µSv for a small group and 14 µSv for a large group – that the results of dose calculations have been evaluated.

The regulatory authorities also stipulate that the risk should be calculated as an annual average of lifetime dose.

As in the IAEA's definitions, the dose commitment from one year's intake has been regarded as an annual dose for the internal exposure, while the external exposure relates to the exposure for the year in question.

In calculations for different scenarios, a probabilistic method has been used for the most part, based on randomization of input data from distributions of the constituent parameter values. The width of the intervals used reflects current knowledge and thereby uncertainty in a given parameter value. A large number of realizations have been carried out where consequences have been calculated for the randomly selected data from the distributions. The result is a statistical distribution of doses as a function of time, where the mean value of the distribution has been used for comparison with the criterion. This is called a conditional risk, since it assumes that the scenario in question has occurred. The unconditional risk is obtained by multiplying by the probability that the scenario actually occurs. In the determination of the total risk, the risks of the scenarios are weighed together, taking into account possible combinations of scenarios.

The reference evolution and the scenario analysis show that the conceivable evolution of the repository is covered by a few probabilistic calculation cases for radionuclide transport. From both a practical and a pedagogical viewpoint, it has therefore been most effective to:

- calculate the conditional risk, i.e. the dose, for each calculation case (this is done in Chapter 9),
- the results from the different calculation cases are weighed together to obtain a total risk estimate (Chapter 10),
- compare the estimated risks to the criteria in the regulations (Chapter 10).

2.6.1 Doses to biota

The concentrations of the various radionuclides in the relevant media, such as soil and water, have been calculated in the dose calculations. The values of these concentrations, which are based on a maximum estimated inflow of the radionuclide in question, have been compared with the published concentrations of the same radionuclides proposed by the ERICA project /ERICA 2008, Beresford et al. 2007/. EMCLs, Environmental Media Concentration Limits, have been determined in the international ERICA project (carried out within the EU's 6th Framework Programme) according to a method described in the previously conducted FASSET project /FASSET 2004, Larsson 2004/.

If the calculated concentrations are lower than these EMCL values, no further analyses need to be done according to the proposal in the ERICA project.

2.7 Documentation and quality assurance

SKB has a quality management system that meets the requirements in ISO 9001:2000. The quality management system includes procedures for project management and safety audit, and these procedures have served as a basis for framing the control documents, or quality assurance systems, that have governed the work in the SFR 1 SAR-08 project.

A number of control documents have been prepared in line with the overall procedures for project management and safety audit. These control documents are summarized in Table 2-1.

Table 2-1. Control documents for the SFR 1 SAR-08 project.

Object number	Title	Document
1	Project Decision SFR 1 SAR-08	1060288
2	Project Plan SFR 1 SAR-08	1062026
3	SFR 1 SAR-08 Risk Analysis	1065336
4	SFR 1 SAR-08 Decision Matrix	1065335
5	Timetable for Long-term Safety	1083039
6	Document Management Plan for SFR 1 SAR-08 Project	1067735
7	SFR 1 SAR-08 Audit Instructions	1064504
8	SFR 1 SAR-08 Audit Plan for Long-term Safety	1064771
9	Quality Audit in the Area of Interdisciplinary Technology	1066951
10	SFR 1 SAR-08 Audit Plan for Co-audit	1064811
11	Template for Review Message	1067591

The project that has produced the present safety assessment has been conducted in accordance with SKB's quality management system. All documents included in the safety analysis report and all background reports produced within the project are subjected to safety audit in accordance with the safety audit instructions. The acceptance criteria on which the audit is based are given in the audit plans prepared for the project. All parts of the safety audit are documented in a traceable manner in accordance with regulatory requirements.

In order to ensure that the safety analysis report meets all requirements on long-term safety in regulations or decisions from regulatory authorities, the project has worked with two requirements documents. These documents list the requirements in regulations and decisions, respectively. The project has worked with these lists in order to ensure that all requirements are complied with and to demonstrate this compliance to the regulatory authorities. The results are presented in Appendices A and B.

There are no control documents in the project for work with calculation models. However, SAR-08's model summary report /SKB 2008/ describes the work that has been carried out for each calculation model to ensure that the results are correct.

A number of background reports have been produced within the framework of SFR 1 SAR-08. Expert assessments made in these reports have been performed by the authors, unless stated otherwise. Information on the author of each chapter or report is provided for reports written by SKB. Each report written within the project has been subjected to factual review by experts, and review messages from these reviews are documented in SKB's document management system.

2.7.1 Data selection

Since no integrated data report is prepared within the framework of SFR 1 SAR-08, input data reports are presented for SAR Long-term Safety in Table 2-2.

Table 2-2. Selection of input data.

Data	Data	Reference
The repository's dimensions		/SKB 2001c/
Waste data, including inventory		/Almkvist and Gordon 2007/
Water flow, near-field		/SKB 2001c, Holmén 2005, 2007, Vidstrand et al. 2007/
Solubility		/SKB 2001c/
Sorption		
	Cement/concrete	/Cronstrand 2005, Cronstrand 2007/
	Bentonite	/SKB 2006c/
	Sand/ bentonite mixture	Values are calculated from sorption values for sand and bentonite, see section 8.4.1
	Sand/gravel	/Cronstrand 2005/
	Porosity, diffusivity, density	/SKB 2001c/
	Diffusivity of bentonite	/SKB 2006c/
Geosphere data		
	Flow-related migration parameters	/SKB 2001c, Holmén 2005, 2007, Vidstrand et al. 2007/
	Sorption	/SKB 2006c/
	Matrix porosity	/SKB 2001c/
	Penetration depth	/SKB 2001c/
	Matrix diffusivity	/SKB 2006c/
Biosphere data		/Bergström et al. 2008/
Radiological data		/Bergström et al. 2008/

3 Identification, prioritization and handling of FEPs

3.1 Introduction

In a safety assessment it is important to identify early on all the factors that are of importance for repository evolution and that should be studied to obtain a good understanding of the repository in the future. This is usually done with the aid of an FEP analysis, in other words an analysis of the Features, Events and Processes that are of importance for the evolution and function of the repository. The FEP analysis for this safety assessment was conducted in two steps. The first step was taken in the SAFE project in 2001 and dealt with the period up until 10,000 years after closure /SKB 2001b/. The second supplementary step comprises a renewed FEP analysis to take into account the longer period covered by this assessment, i.e. up to 100,000 years after closure /Gordon et al. 2008/.

The FEP analysis in the SAFE project was arrived at during meetings with various experts, with the aid of interaction matrices /SKB 2001a/. The method is used to systematically identify processes and interactions in the system. At the same time, the importance of these processes and interactions for the evolution of the system is evaluated (prioritization). Three coupled matrices were used to describe the repository system in SFR 1: one for the repository itself, one for the geosphere and one for the biosphere. The work was documented in a database. The contents of the matrices were checked against an international FEP database /NEA 1997/ to ensure that all relevant FEPs had been included. The NEA database also includes external features, events and processes (EFEPs) that are not included in the matrices. These EFEPs, together with a review of previous safety assessments, constituted the basis for scenario selection in the SAFE project.

In the supplementary study, the work was based on the definition of different types of scenarios according to SKIFS 2002:1 (main scenario, less probable scenarios and residual scenarios, see section 7.2). The prioritization of the importance of the interactions was re-evaluated to apply for the main scenario and less probable scenarios, as well as for the longer time perspective. Furthermore, a cross-check was made against new government regulations (SKIFS 2002:1, SSI FS 2005:5) and the regulatory review of the SAFE project /SSI/SKI 2003/.The interaction matrices were also cross-checked against the FEPs arrived at for SFR 1 on behalf of SKI /Miller et al. 2002/. The supplementary study also included a sorting of external FEPs into those that are of no importance for the analysis, those that need to be taken into consideration in the selection of the main scenario and less probable scenarios, and those that need to be taken into consideration in the selection of residual scenarios.

This chapter first describes how FEPs and EFEPs are identified and prioritized (section 3.2). Then the contents of the matrices and identified EFEPs are then presented in tables (section 3.3). Finally, the way in which the qualitative information in the interaction matrices is transferred to the quantitative analysis via information flow diagrams is described (section 3.4).

3.2 Identification and prioritization

3.2.1 Identification and prioritization for the first 10,000 years

The FEP analysis that was carried out within the SAFE project for the first 10,000 years comprises the basis for the FEP analysis in this safety assessment. In the SAFE project, there was a great emphasis on finding all FEPs and interactions between processes that are of importance for the future evolution of the repository. The work was carried out with the aid of interaction matrices, which are based on a method originally developed by /Hudson 1992/. This and similar methods have been developed over the years /Chapman et al. 1995, Skagius et al. 1995/ and are based on systematic and documented expert judgements with a focus on identifying interactions between different processes. The contents of the matrix were cross-checked against the then-current version of the NEA FEP database (version 1.0) /NEA 1997/.

Interaction matrices

The first step in constructing an interaction matrix is defining the variables that are needed to describe the properties and states of the system over time. These variables are entered into the diagonal elements in the interaction matrices. Different processes influence the variables, and conversely the outcome of different processes is dependent on the value of the variables. These interactions (processes) are described in the other elements in the interaction matrix. The convention that is used is that the interactions that are listed in a column in the matrix affect the diagonal element in the column, and the interactions on a given row are affected by the state in the diagonal element on this row, see Figure 3-1. Finally, different interactions can be of differing importance. This is indicated by colour coding in the matrix.

In order for the studied system to be described, it must be delimited and possibly divided into subsystems. The system for SFR 1 comprises the engineered parts of the repository, i.e. different types of solidified and non-solidified waste, barriers, various rock vaults and tunnels, and the rock and the biosphere that may be directly affected by releases from the repository. For practical reasons the system is divided into three different subsystems: repository, geosphere and biosphere, each of which is documented in an interaction matrix. Each matrix also contains interactions between the subsystems in special diagonal elements known as boundary elements. The three different interaction matrices can therefore be regarded as parts of a larger composite matrix covering the entire system for SFR 1. During the work of constructing the matrices, particular attention was devoted to the interfaces between the subsystems in order to ensure that no direct dependencies between states in different subsystems had been overlooked.

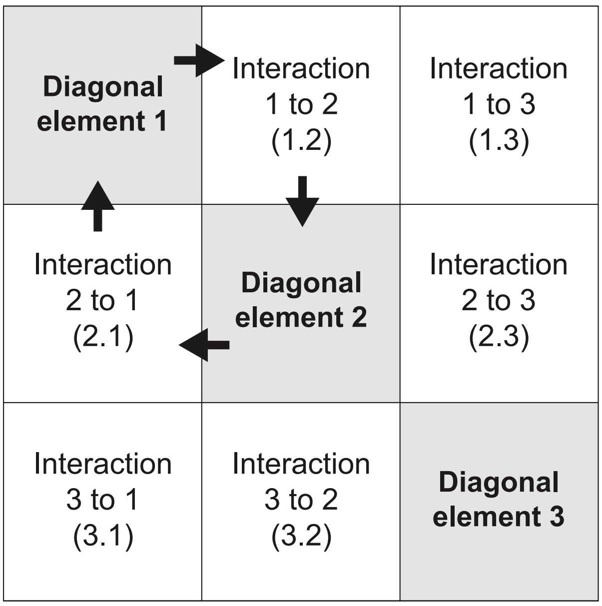


Figure 3-1. *Principle of an interaction matrix.*

The choice of diagonal elements (variables) is based on the thermal, hydrogeological, hydrogeochemical and mechanical states of the subsystems. Furthermore, the physical states (e.g. density, porosity, permeability) of the different subsystems need to be described. In order to keep the matrices from becoming large and unwieldy, several variables can be put in the same diagonal element under a common heading. This applies, for example, to "groundwater composition", which can be divided into several specific variables (concentrations of different substances, colloid content, dissolved gas content, etc). The state in a subsystem is characterized at any given moment by a set of variables. Together the variables should characterize the system well enough to serve as a basis for a safety assessment. Certain variables, such as temperature and groundwater composition, are used or determined directly in the calculations, while others serve as a basis for deriving important properties of the system. All variables are affected by one or more processes, and all processes are affected by one or more variables. As a result, the variables may vary in both time and space. The state of the geosphere is characterized, for example, by its temperature, which varies in time and space, by its fracture geometry (which varies greatly in space, but less so in time), by groundwater flow (which varies in both time and space), groundwater composition, rock stresses etc.

Within the repository subsystem, the variables can be divided into those that describe the physical state of waste forms, barriers and other structures, and those that describe the hydrogeological, hydrogeochemical, mechanical and biological state of the repository. The description of the geosphere includes the state of the rock (mainly permeability), hydrogeology, hydrogeochemistry, mechanics and biology. In the description of the biosphere, the focus is on the different components in the food chains, but the description also includes water flow, water composition and the physical properties of the soil layers.

A large part of the analysis is concerned with radionuclide transport, which is also important for the evaluation of the repository's safety. Radionuclide transport is really the combined result of a series of hydraulic and chemical processes and is therefore covered by the processes in these categories. If chemical and hydraulic conditions as well fracture geometry are known, radionuclide transport can also be described. Since radionuclide transport is such an important part of the safety assessment, it constitutes its own diagonal element in the interaction matrix.

Identification of the interactions was done systematically by going through all diagonal elements and answering the question of whether there is any process or event that is dependent on the variable in the diagonal element and that can affect the state in another diagonal element. Only direct interactions between variables are described. The indirect influence that follows from the fact that one variable affects another, which in turn affects a third variable, is not described; indirect influence is obtained as a result when the dependency chains in the matrix are followed.

In several cases there is no reasonable possibility that two diagonal elements directly affect each other via an interaction. In these cases the matrix element is left blank. For example, the states in two repository parts physically isolated from each other cannot affect each other directly but rather only via e.g. groundwater flow and altered composition of the groundwater in the system.

For a given scenario, an assessment is then made of how important different interactions are for the results of the safety assessment. This prioritization was done according to a predetermined scale, see Table 3-1. A colour scale (pink, red, yellow and green) is used in the graphic representation to illustrate this.

Table 3-1. Scale for prioritization of the interactions in the matrices.

Priority No	Colour	Description
4	Pink	Important – but only during the saturation phase
3	Red	Important – must be included (or at least evaluated) in the safety assessment
2	Yellow	Unclear – the process may need to be included in the assessment, but further study is required to determine its importance
1	Green	Unimportant – the interaction exists but can be neglected
0	Blank	No interaction found

The priorities for the base scenario in the SAFE project were determined in a series of meetings attended by different experts.[1] The experts who made the judgements were largely the same as the ones in the project group for the whole SAFE project (see list in the SAFE project's scenario report /SKB 2001b/. The expert group was augmented in areas where special expertise was deemed necessary (for instance bentonite evolution, microbial states or ecosystem evolution).

The work with interaction matrices was documented in a database. The documentation in the database comprises a brief description of the process, a description of the variable that affects the process, the variable affected by the process, priority and reason for priority, and any references. The date (version management) of the judgement and who made the judgement were also documented.

Cross-check against NEA FEP database

In order to check the completeness of the interaction matrices, the contents were cross-checked against the NEA's international FEP database (version 1.0) /NEA 1997/. The FEP database is a compilation of FEPs that have been considered in seven safety assessments conducted in different countries. After the cross-check had been performed against the database, the interaction matrices were supplemented.

The check was done stepwise, as illustrated in Figure 3-2. First the NEA FEPs that are not relevant for SFR 1 were culled. They may, for example, relate to another type of waste or other geological environments. After this culling, FEPs were classified into those that could potentially be included in the interaction matrices and those that are potentially important external features, events or processes, EFEPs. The FEPs that could be included in the interaction matrices were divided into three groups: those that are already included in the matrices, those that need to be added to the matrices, and those that are of such little importance that they do not have to be added to the matrices.

The cross-check was carried out by persons who had participated in the work of constructing the interaction matrices. The work is documented in appendices in the SAFE project's scenario report /SKB 2001b/.

[1] The SAFE project was conducted before the regulatory requirement (SKIFS 2002:1), stating that the assessment must include a main scenario that takes into account the most probable changes in the repository and its environs, was published. The base scenario in the SAFE project was chosen so that a) it was probable and b) it could serve as a suitable point of reference on which it was possible to superimpose the influence of other scenarios.

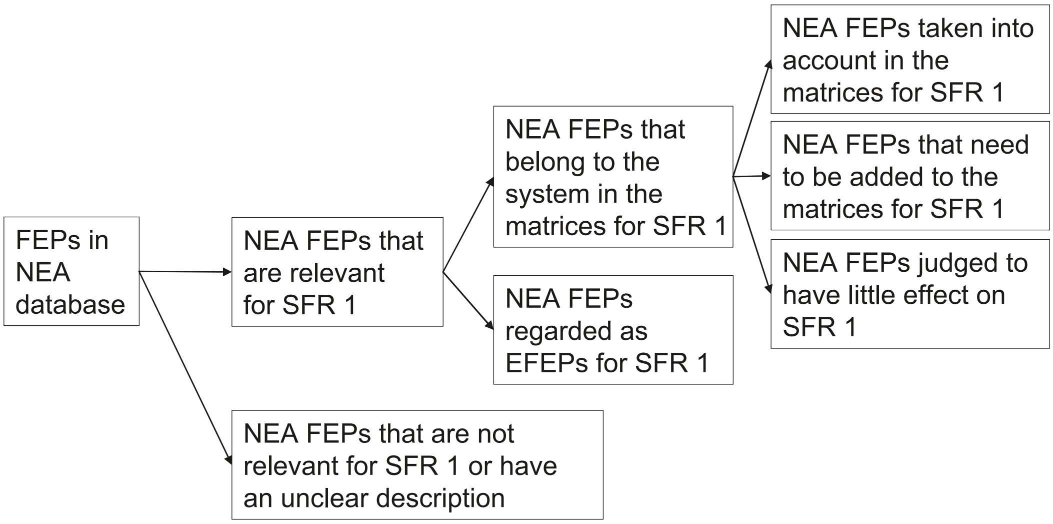


Figure 3-2. *Flow chart for cross-checking against the NEA FEP database.*

The NEA FEP database (version 1.0) contains 1,261 FEPs. The results of the cross-check were that:

- Approximately 300 FEPs were judged to be irrelevant or have an unclear description and were therefore dismissed.
- Approximately 700 FEPs were classified among those that should be included in the interaction matrices. Nine of these were missing from the interaction matrices set up for SFR 1, so they were added to the matrices.
- More than 200 FEPs were classified as EFEPs.

It was also noted that the interaction matrices contained many FEPs that were not included in the NEA database.

The latest version of the NEA FEP database (version 2.1) includes FEPs from ten projects, compared with seven in the version used for the SAFE project. In the supplementary study /Gordon et al. 2008/, a cross-check of the interaction matrices was made against the new information judged to be most important in the latest version of the NEA FEP database. The cross-check was done for the FEPs that had been arrived at for SFR 1 on behalf of SKI /Miller et al. 2002/. The results of the cross-check were that no more FEPs needed to be added to the matrices /Gordon et al. 2008/.

Identification of external FEPs

In the SAFE project /SKB 2001b/, EFEPs were identified by going through some of SKB's most recent safety assessments and the NEA FEP database. In the SAFE project, EFEPs are equated with scenario-initiating events and conditions. The selection of relevant EFEPs was based on:

- the scenarios that had been described in previous safety reports for SFR 1 /SKB 1993/ and analyzed in other safety assessments performed by SKB /SKB 1999a, 1999b/,
- the FEPs in the NEA's international database /NEA 1997/ that had been classified as EFEPs for SFR 1, see above.

After the screening, the EFEPs were divided into six groups:

- natural climate change,
- human-induced climate change,
- initial defects or other fundamental uncertainties about the initial state,
- tectonics,
- human actions,
- others.

The complete list of sorted EFEPs for the first 10,000 years is included as an appendix to the SAFE project's scenario report /SKB 2001b/.

3.2.2 Prioritization for entire period of 100,000 years

In the supplementary FEP analysis /Gordon et al. 2008/, the prioritization of the importance of FEPs and EFEPs in the previous analysis /SKB 2001b/ was re-evaluated based on the longer time perspective, 100,000 years. This re-evaluation also took into consideration the new forecast of the inventory /Almkvist and Gordon 2007/, new government regulations (SKIFS 2002:1, SSI FS 2005:5) and comments from the regulatory review of SAFE /SSI/SKI 2003/. All interactions deemed to be unimportant (green), and many of those deemed to be of unclear importance (yellow) in the previous analysis /SKB 2001b/ were re-evaluated. In SAFE, the prioritization was done for the base scenario, while the updated prioritization was done for the main scenario and less probable scenarios. This difference is due to the fact that the matrices are also used to select a main scenario and less probable scenarios, see Chapter 7.

In addition to the re-evaluation of priorities, a review was also made of the contents of the FEPs arrived at for SFR 1 on behalf of SKI /Miller et al. 2002/ in order to ensure that nothing important is omitted in the interaction matrices.

The re-evaluation of the priority of the interactions resulted in the fact that approximately 50 additional interactions were judged to be important and had to be included in the analysis. Most of these are related to the greater temperature changes that are expected, due to the fact that the safety assessment covers a longer time span and permafrost and glaciation therefore have to be taken into account. The reasons for the revised priorities and the interaction matrices with the priorities that apply for the main scenario and less probable scenarios are presented in /Gordon et al. 2008/. The interaction matrices are also shown in Appendix D.

The selection of scenarios in this safety assessment (Chapter 7) is based on safety functions (Chapter 5). The expected evolution of the selected safety functions constitutes the main scenario. Deviations from the expected evolution of the safety functions lead to other scenarios. In order to systematically check whether a safety function can deviate from what is expected, a review is made of matrices and EFEPs. In the supplementary FEP analysis /Gordon et al. 2008/, an assessment was made of which EFEPs are of importance for scenario selection and which are of no importance for scenario selection. As a preliminary step to scenario selection, the diagonal elements that can be affected by each EFEP that can be of importance for the selection of the main scenario and less probable scenarios were identified.

3.3 Description of FEPs

This section presents the contents of the matrices and the tables of EFEPs resulting from the identification and prioritization described in the preceding sections. First the contents of the diagonal elements are presented, then a summary description is given of the processes that have been judged to be important for repository evolution. This constitutes a basis for what needs to be described in the presentation of the repository and the evolution of its environs in Chapter 6. Finally, the tables of EFEPs that constitute a basis for the scenario selection presented in Chapter 7 are presented.

3.3.1 Diagonal elements of interaction matrices

The diagonal elements, which contain variables describing properties and conditions, are presented in brief below. A more detailed description, together with a list of variables, is found in Appendix D.

The repository matrix

The repository matrix consists of 18 diagonal elements /SKB 2001b/. The first nine describe the physical state (the properties) of different parts of the repository, subdivided as follows:

- Waste/cement
- Waste/bitumen
- Waste/non-solidified
- Concrete packaging
- Steel packaging
- Concrete backfill
- Concrete structures
- Bentonite barriers
- Vaults and backfill

The following diagonal elements describe the THMC state (thermal, hydraulic, mechanical and chemical) in the repository:

- Water composition
- Hydrology
- Gas
- Temperature
- Stress conditions
- Biological state
- Radionuclides and toxicants

The following diagonal elements constitute boundaries against the geosphere matrix:

- Tunnels (boundary condition)
- Repository rock (boundary condition)

The geosphere matrix

The geosphere matrix consists of 18 diagonal elements. The first four of these constitute the boundary against the repository matrix:

- Silo
- BMA
- BTF
- BLA

The following diagonal elements describe the physical properties of the geosphere:

- Tunnels/boreholes/backfill
- Plugs
- Repository rock matrix
- Repository rock fracture system
- Rock (rock matrix and fracture system).

The following diagonal elements describe the THMC state in the rock:

- Water composition
- Hydrology
- Gas
- Temperature
- Stress conditions
- Biological state
- Radionuclides and toxicants

The following diagonal elements constitute the boundary against the biosphere and the external environs:

- Biosphere
- External rock

The biosphere matrix

The biosphere matrix consists of 15 diagonal elements. The first two of these constitute the boundary against the geosphere matrix and the physical properties of the biosphere:

- Geosphere
- Quaternary deposits

The following diagonal elements describe the components in the ecosystems:

- Primary producers
- Decomposers
- Filter feeders
- Herbivores
- Carnivores
- Humans

The following diagonal elements describe the THMC state in the biosphere:

- Water in Quaternary Deposits
- Surface water, i.e. all surface waters except water in Quaternary deposits
- Water composition, both water in Quaternary deposits and surface waters
- Gas/Atmosphere
- Temperature
- Radionuclides and toxicants

The following diagonal elements constitute the boundary against the external environs:

- External conditions

3.3.2 Processes

In the SAFE project's scenario report /SKB 2001b/, a description is given of the processes deemed to be important for repository evolution during the first 10,000 years (mainly those coded pink or red). Other processes are described briefly in the complete documentation of the interaction matrices in the SAFE project, which is stored in a database. These brief descriptions of processes in the repository matrix and the geosphere matrix can also be found in the appendix to the supplementary study /Gordon et al. 2008/. Following is a summary of the most important processes in the SAFE project's scenario report /SKB 2001b/ and the processes whose priority has been upgraded in the supplementary study covering 100,000 years /Gordon et al. 2008/

(primarily those coded pink or red). The processes that have been upgraded in priority are above all mechanical stresses due to volume changes when water in different components freezes, and stress changes in conjunction with glaciation when an ice sheet forms and melts.

The purpose of this section is to report the most important results from the FEP analysis as a basis for what needs to be described in the presentation of the evolution of the repository and its environs in Chapter 6.

Processes in the repository matrix

The repository matrix comprises solidified and non-solidified waste, waste packaging, concrete structures, bentonite barriers, vaults and backfill.

The physical properties of waste forms, waste packaging, the bentonite barrier around the silo and various structures are affected by numerous processes such as *recrystallization*, *water uptake, chemical and microbial degradation, metal corrosion, dissolution/precipitation, formation of different corrosion products with volume changes, radiation effects and microbial activity*. Of these, it is mainly water uptake – resulting in cracking of bitumen, transformation of concrete, possibly with expansion, metal corrosion and bentonite swelling – that has any appreciable influence on the evolution of the barriers.

By *water composition* is meant its content of solutes and colloids as well as dissolved gas. Water composition changes as a result of *advection* and *mixing*. Concentration differences are equalized via *diffusion*. Chemical processes that affect water composition are *dissolution/precipitation, sorption* and *ion exchange reactions*. Sorption probably has a negligible effect on the content of the water's main components but is important for controlling the concentration of substances occurring in small quantities, such as radionuclides and complexing agents. Chemical and microbial *degradation* or organic substances affects the composition of the water, as does *colloid formation*. Special attention should be paid to the degradation of cellulose, since it can give rise to *complexing agents* (isosaccharinic acid, ISA). *Metal corrosion* and the resultant corrosion products affect the chemical composition of the water, and corrosion can also cause gas formation. Mechanical erosion of different repository components (concrete parts, backfill material, bentonite backfill etc) due to water flow could theoretically cause *colloid formation*, but the process is probably of less importance than chemical colloid formation.

The water flow through the repository is determined by permeability of the various structural parts and the components in the repository, as well as by the hydraulic gradient. If gas is present at the same time, this gives rise to a *two-phase flow*, where both the water and the gas flow are affected by the relative degree of saturation of each phase. Two-phase flow as a process can be of importance in the analysis of gas flows, but can be neglected in the analysis of post-closure repository saturation, since saturation takes place very rapidly /Holmén and Stigsson 2001a/. High *gas pressures* caused by entrapped gas can give rise to a locally elevated groundwater pressure and therefore be a driving force for the water flow out of such inclusions. Concentration gradients can also cause water flow via *osmosis*, but the process is of no importance except for the description of the degradation of bitumen. The magnitude of the water flow in the repository is determined to a high degree by the surrounding groundwater flow (*boundary conditions*).

The most important process for generating gas, especially hydrogen, is *corrosion* of different metals (iron, aluminium, zinc). Gas can also be generated by degradation *of organic material*, including microbial degradation. If the necessary conditions exist for *radiolysis* of water, hydrogen is also formed. But the radiation levels (dose rates) in SFR 1 are so low that this process is without importance. *The gas flow* through the repository is determined by the permeability (pore structure) of the repository parts and the pressure distribution. The volume of gas is dependent on its quantity and pressure, which is in turn affected by the water pressure and the extent to which newly formed gas is prevented from escaping from the repository system.

There are few heat-generating processes in SFR 1. *Corrosion* of aluminium could be a possible exception, but has been found to be of no importance /Moreno et al. 2001/. Heat transport can essentially be expected to take place via *heat conduction*, which is governed by the thermal conductivity and heat capacity of the materials. The temperature of the repository will be determined almost entirely by the exchange of heat with the surrounding rock and groundwater. The impact of the repository on the temperature is negligible.

The repository parts will be subjected to *mechanical stresses*. The following is of particular interest to study:

- stress on the concrete structures due to corrosion and volume changes, such as ettringite formation,
- volume changes in bitumen due to water uptake,
- volume changes when water in different components freezes.

Volume changes affect the *stress distribution* in the relevant repository components, which can in turn lead to *fracturing*. Groundwater flow can cause mechanical *erosion* of the bentonite. Any changes in the geometry of the bentonite barriers (for example due to degradation of the silo wall) affect *swelling* and thereby the swelling pressure in the bentonite. The water pressure and the gas pressure further affect the mechanical stress state in the different parts of the repository. If gas is generated that cannot escape, this can lead to considerable pressure and stress build-up. Finally, the repository will be affected by any deformations in the rock and by *cavings* (falling blocks, propagated rock movements, earthquakes etc). Conversely, the stability of the rock is affected by the capability of the interior of the tunnels to balance the stresses that otherwise cause deformations in the rock.

The microbial activity in the repository is determined primarily by the availability of organic material in the repository. Microbial activity is also affected by the groundwater flow. Post-closure microbial activity in SFR 1 is judged to be little /Pedersen 2001/.

Several processes influence *radionuclide transport* (migration) within and out of the repository. Radionuclides are transported with the groundwater flow (*advection*) and are also subjected to *dispersion* and *mixing*. In repository parts with little groundwater flow, for example inside waste packaging or inside the pits in the silo or in BMA, *diffusion* is the most important transport mechanism. *Sorption* is the most important retarding mechanism. The concentration of different radioactive substances is too low to make *dissolution/precipitation* an important retarding function. In the cement-rich environments in the repository, the calcium concentration is high, which counteracts the formation of colloids /Hunter 1987/. *Colloid transport* is therefore not a factor in these parts of the repository, but may occur in repository parts with a low cement content (BLA) or in the rock. Chemical, mechanical and microbial *degradation* of bitumen affects radionuclide release from the bitumen waste. Gaseous radionuclides that are not dissolved in the water will be transported as gas, and with very little retardation. The radionuclides are transformed by *radioactive decay* to stable, non-radioactive substances.

Processes in the geosphere matrix

The interaction matrix for the geosphere includes the rock matrix and the fracture system in the rock, as well as tunnels, boreholes and plugs.

The available pore space in backfilled access tunnels and boreholes can, in principle, be affected by processes such as *dissolution/precipitation*, *filtration* of particles in the water and *microbial activity*. If the rock support degrades, *cavings* can also occur, but this is prevented to the extent there is backfill that can provide support. None of the processes is important, since the access tunnels do not have any important barrier function. The barrier function is in the plugging.

The final design of the plugs that will be used in e.g. access tunnels has not yet been determined. The material in the plugs can, however, be assumed to be concrete and bentonite (or another clay). A proposed design of the plugs in the access tunnels is illustrated in Figure 4-9.

If the concrete parts of the plugs degrade, entrapped bentonite (if present) may expand due to *water uptake* and *swelling* out into the tunnel backfill. The chemical properties, pore volume and structure of the bentonite and the concrete can change due to *dissolution/precipitation*. If the concrete in the plugs degrades, this can lead to *fracturing* in the concrete.

Fractures and fracture zones in the rock occur in all sizes from regional fracture zones down to microfractures in the "rock matrix" or the "intact rock", as it is known in rock mechanics, see for example /Andersson et al. 2000/ for a description of the nomenclature. *Dissolution/precipitation* affects both the size of the fracture openings and the mineral composition on the fracture surfaces. For SFR 1, special attention needs to be devoted to whether the cement-rich environment causes so many hydroxide ions (OH^-) to be released that *reactions* with calcite and carbonate can give rise to secondary minerals. Changes in the rock stresses can also affect the size of the fracture openings. Future *stress changes* are expected as a result of expansion of the water when it freezes, earthquakes and the extra load exerted by an ice cap. *Microbial activity* can alter the chemical environment and could also clog various voids, but this activity is too low for this process to require detailed study.

Groundwater composition also includes colloid content and content of dissolved gas and is changed due to *advection, mixing* and *diffusion* in the rock matrix. Chemical processes that affect water composition are *dissolution/precipitation, sorption* and *ion exchange reactions*. Sorption probably has a negligible effect on the content of the water's main components but is important for controlling the concentration of substances occurring in small quantities, such as radionuclides and complexing agents. The composition of the water in the rock will be determined to a great extent by the *boundary conditions*, i.e. the composition of the groundwater flowing into the repository area, which is in turn dependent on the "natural" composition of the groundwater and its variation and the changes in this composition caused by the repository. The first big change in composition occurs when land uplift has proceeded so far that the groundwater in the repository comes from infiltrating fresh water. *Low ionic strength* in glacial meltwater affects the stability of the bentonite. The other chemical processes that occur in the rock around SFR 1 can probably be neglected.

The groundwater flow in the rock is determined by the permeability of the fracture system and the hydraulic driving forces. For saline groundwater it is necessary to take into account both the pressure distribution of the groundwater and its density distribution (buoyancy). In the case of SFR 1, however, the salinities are relatively low and the ongoing process of *land uplift* means that they are transient. Calculations /Stigsson et al. 1998/ show that the density effects can be neglected, but that it is important to take land uplift into consideration. The flow of gas through the rock will in principle be a *two-phase flow*. In calculating the time for *resaturation* of SFR 1, the effects of the gas flow can be neglected. The groundwater flow in the rock is connected to the flow inside the repository and should be analyzed as a whole. The driving forces (topography and land uplift) are determined by the external boundary conditions.

Gas transport is determined by the permeability of the rock and the tunnels to gas. The driving force is gas pressure and buoyancy. In crystalline rock, gas permeability is usually considerable and calculations /Thunvik and Braester 1986/ show that all gas that will be formed inside SFR 1 will be able to reach the surface quickly and without appreciable resistance. The gas pressure is determined in part by the water pressure, but effects of two-phase flow in the geosphere can be neglected. At high pressures, generated *gas will dissolve* in the water, but this process will scarcely be important in SFR 1. The most important source of gas is the gas that is formed in the repository and transported out of it to the geosphere.

The mechanical state of the rock is determined by *stress distribution* and *deformation state*. If the strength of the rock is exceeded, *failure* occurs. The deformation properties of the rock depend on the properties of the intact rock and the fracture geometry. The *load of the ice cap* in conjunction with future glaciation is expected to exert a great external force. Changes in temperature affect the stress state, and especially *temperature changes* that lead to freezing of the groundwater. The stability of the tunnel walls is also affected if the *rock support* (rock bolts and shotcrete) *degrades*. The stability of the rock around the tunnels will also be affected by the mechanical properties inside the tunnels, and above all by whether the tunnels can resist *cavings*.

In the same way as in the repository, microbial activity in the rock is judged primarily by the availability of organic material. The state is also affected by the groundwater flow. Microbial activity is low in the rock /Pedersen 2001/.

Radionuclides that are dissolved in the groundwater are transported through the rock by the flowing groundwater via *advection and dispersion*. Radionuclides can also *diffuse* into the microfractures in the rock matrix and be retarded there by *sorption*. The efficacy of this retardation is determined by the transport resistance, see e.g. /Andersson et al. 1998/. Diffusivity in the rock matrix is dependent on the properties of the rock, but is also substance-specific due to processes such as *anion exclusion*. Diffusivity is thereby also dependent on the composition of the water (mainly its ionic strength). Sorption is dependent on the mineral composition of the rock, but to a higher degree on the *speciation* of different substances. This means that sorption is also strongly dependent on the composition of the water. The presence of any *complexing agent* affects sorption capacity. *Dissolution/precipitation* will in practice not be important retarding mechanisms, since the radionuclides will occur in concentrations far below the solubility limit of the substances. The presence of *colloids* in the groundwater could reduce the transport resistance, since the substances that have sorbed on the colloids cannot diffuse into the rock matrix. The radionuclides that are released from the repository in *gaseous form* will be transported rapidly and without resistance through the rock. The radionuclides are transformed by *radioactive decay* to stable, non-radioactive substances.

Processes in the biosphere matrix

The biosphere matrix includes Quaternary deposits, primary producers (plants), decomposers, filter feeders, herbivores, carnivores and humans.

The Quaternary deposits are affected by affected by *bioturbation*, where for example worms homogenize the upper soil layers, and by *erosion* caused by wind, ice, flowing water and wave-washing. Deposits are formed by *sedimentation* during land uplift and thereby affect the topography.

The primary producers of organic material (e.g. plants and algae) make use of photosynthesis. Likelihood of *settlement* and *population size* are affected by the properties of the substrate and the availability and movement of water, as well as by the composition of the water. *The temperature* will affect settlement and population size, especially in connection with future permafrost and glaciation. The primary producers comprise a *food source* for other organisms. The availability of light for photosynthesis is affected by *insolation* and by how much the light is *attenuated* in the surface water. Uptake of radionuclides takes place via the water. Possible radiological effects caused by *internal exposure* of the primary producers depend on the concentration and type of radionuclides in them. *External exposure* is dependent on the concentration of radionuclides in the surrounding environment.

Organisms that decompose dead organic material include bacteria, worms, fungi, etc. *Settlement* and *population size* are affected by the properties of the substrate and the availability and movement of water, as well as by the composition of the water. Most macroscopic organisms of this type (e.g. worms) prefer soft substrates such as sand, clay, mud or soil. The macro-decomposers also *consume* soil. The availability of degradable organic material is dependent on the production and mortality of other organisms. *Uptake* of radionuclides mainly takes place via consumption of organic material and soil and via water. Possible radiological effects caused by *internal exposure* of the decomposers depend on the concentration and type of radionuclides in them. *External exposure* is dependent on the concentration of radionuclides in the surrounding environment.

Filter feeders include mussels, sponges, insect larvae etc that filter water to obtain food. Likelihood of *settlement* and *population size* are affected by the properties of the substrate and the availability and movement of surface water, as well as by the composition of the water. Many filter feeders, such as blue mussels, prefer hard substrates, while a few (insect larvae) prefer soft substrates. Amounts and types of filter feeders are affected to a high degree by the water's content of nutrients, its salinity and its composition in other respects. *Uptake* of radionuclides takes place via water and food intake. Possible radiological effects caused by *internal exposure* of the filter feeders depend on the concentration and type of radionuclides in them. *External exposure* is dependent on the concentration of radionuclides in the surrounding environment.

Examples of herbivores are snails, insects and cattle. They can be found both on land and in water, which means that the species composition in a given area is affected by land uplift. Likelihood of *settlement* and *population size* are determined primarily by the availability of suitable food plants, but also by the supply of drinking water and the composition of the water, as well as by the availability of suitable habitats. Herbivores consume soil while eating plants. *Radionuclide uptake* takes place mainly via food, mistakenly consumed soil and water. Possible radiological effects caused by *internal exposure* of the herbivores depend on the concentration and type of radionuclides in them. *External exposure* is dependent on the concentration of radionuclides in the surrounding environment.

Organisms that eat other animals (carnivores), i.e. predators, may include various species of fish, birds of prey (e.g. white-tailed eagle), seal or fox, but also mosquitoes and ticks. Likelihood of *settlement* and *population size* are determined primarily by the availability of prey. *Uptake* via food is the most common exposure pathway. Possible radiological effects caused by *internal exposure* depend on the concentration and type of radionuclides in the predators. *External exposure* is dependent on the concentration of radionuclides in the surrounding environment.

The number of humans in the area and their *distribution* is determined to some extent by the environment, via factors such as availability of water, suitable settlement sites and the location of suitable agricultural land. However, other external factors entirely can be more decisive in determining where humans will be found in the future. *The availability* of and the *selection* of locally produced food will, along with eating habits, be of great importance for intake of radionuclides that have spread in the biosphere. Normally, fish and crustaceans are the only aquatic animals that man eats. Use of locally produced building materials can affect the chances of *external exposure*. The availability of usable surface water and groundwater affects the magnitude of possible abstraction and other water use. Water is used for drinking as well as for bathing, washing and irrigation. Surface water can be used directly for e.g. bathing. Possible radiological effects caused by *internal exposure* depend on the concentration and type of radionuclides that enter the body via food, drink and inhalation. A special case that leads to high exposure is inhalation of smoke from peat fires. *External exposure* is dependent on the concentration of radionuclides in the surrounding environment.

The groundwater flow in the Quaternary deposits is affected by their *water permeability* and conditions for groundwater recharge. Groundwater recharge is controlled by *precipitation* and *evapotranspiration*, but also by the extent to which the groundwater can be received in the deposits. Water flow and quality are affected by *well abstraction*. The groundwater flow is affected by groundwater flow in the *environs* and in the surrounding rock. The groundwater flow is affected by the fact that parts of the Quaternary deposits and the environs freeze in conjunction with permafrost and glaciation. Taliks, i.e. unfrozen zones, will have a relatively high flow, while there will be no flow in frozen parts of the Quaternary deposits.

Surface water turnover above sea level depends on the magnitude of *runoff* and on the topography of lakes and watercourses. Groundwater recharge and discharge mainly affect the composition of the surface water. The composition and temperature of the surface water affects its density and thereby stratification and *mixing* in lakes and in the sea. *The wind* affects wave patterns and *currents* in the water. On a very large scale, the coriolis force also affects the ocean currents. Changes in seal level will affect the occurrence of lakes and watercourses in the area, since new ones will be formed when the shoreline declines. The flow and turnover of surface water is also affected by *water abstraction*.

The composition of the water is dependent on how waters of differing composition *flow* and *are mixed*. The composition is also affected by whether particulate matter is *resuspended*. *Uptake* and *excretion* from primary producers, and above all from decomposers, affects the composition of the water, for example uptake of nutrients and carbon dioxide (by primary producers) or oxygen (by decomposers) and excretion of oxygen (by primary producers) or carbon dioxide (by decomposers). The presence of decomposers in particular affects the particle content of the water. The composition of the water is also dependent on the *exchange* with the external environment and the exchange with the groundwater in the rock.

By gas is meant all gas in the biosphere, including the air in the atmosphere and the gas entrapped in various voids. The composition of the gas is mainly dependent on how the gas is *transported* (mainly with the wind) and *mixed*. Gas composition is thereby determined primarily by what is transported to the area with the wind. Very locally, gas composition is affected by various gas formation processes and *releases* from the rock or the soil of e.g. hydrogen, carbon dioxide, methane, radon or hydrogen sulphide. The presence of dust in the air is affected by *resuspension* of particles from the Quaternary deposits.

The temperature in the biosphere is affected by the following factors: *heat storage capacity*, *heat convection* and *sunlight absorption* (which varies depending on factors such as the particle content of the water). But the temperature is mainly determined by conditions in *the environs* (boundary conditions).

A number of processes affect the concentrations of radionuclides released from the geosphere with groundwater and gas. The radionuclides are transported with *the flowing water* in different parts of the biosphere, and the concentrations are determined by *mixing* between waters with different concentrations of radionuclides. The radionuclides can *sorb* on mineral surfaces in the Quaternary deposits. Radionuclides are *taken up* by the different organisms and carried further via the food chains. If *excretion* is less than uptake, the radionuclides will be *accumulated* in the organisms. The concentrations are also affected by the *growth rate* of the different organisms, but the process is neglected since it entails that the concentrations would be lower than if it is assumed that the quantity of a given organism is constant. The radionuclides are transformed by *radioactive decay* to stable, non-radioactive substances.

3.3.3 External FEPs

The prioritization of EFEPs that was done in the supplementary study /Gordon et al. 2008/ and was briefly described in section 3.2.2 resulted in a table of EFEPs that need to be taken into consideration in the selection of the main scenario and less probable scenarios, see Table 3-2, and a table of EFEPs that need to be taken into consideration in the selection of residual scenarios, see Table 3-3. The selection of scenarios is based on safety performance indicators presented in Chapter 5, but the interaction matrices and these tables of EFEPs comprise complementary background material in the selection of scenarios, see Chapter 7.

Table 3-2 also shows, as a preliminary step to the selection of main scenario and less probable scenarios, the diagonal elements that can be affected by each EFEP in Table 3-2. Since the interactions in the biosphere matrix do not directly affect the safety functions, the biosphere matrix has been short-circuited. Some EFEPs that would have a binary interaction with the biosphere (for example climate change) have therefore been treated as if they have a binary interaction with the geosphere matrix. Many interactions with the repository matrix are not binary, but go via the geosphere matrix.

Table 3-2. EFEPs judged to be important in the selection of the main scenario and less probable scenarios /from Gordon et al. 2008/.

	EFEP	Number in NEA database	Diagonal element directly affected by EFEP
Climate change	Future climatic conditions	K 10.04	GEO10, GEO11, GEO13, GEO14
	Climate change	A 2.07, A 3.024, W 1.061, A 1.12, H 3.1.2	GEO10, GEO11, GEO13, GEO14
	Intensification of natural climate change	H 3.1.4	GEO10, GEO11, GEO13, GEO14
	Permafrost	J 5.17, S 059, K 10.13, W 1.063	GEO10, GEO11, GEO13
	No ice age	J 6.10, N 1.3.7	GEO10, GEO11, GEO13
	Tundra climate	K 10.05	GEO10, GEO11, GEO13
	Warmer climate – equable humid	K 10.09	GEO10, GEO11, GEO13
	Warmer climate – seasonal humid	K 10.08	GEO10, GEO11, GEO13
	Glacial climate – Glaciation	K 10.06, A 3.057, A 1.38, A 2.30, J 5.42, N 1.3.6, S 047, W 1.062	GEO10, GEO11, GEO13, GEO14
	Exit from glacial / Interglacial cycling	H 3.1.3	GEO10, GEO11, GEO13, GEO14
	Ice sheet effects	K 10.16	GEO10, GEO11, GEO13, GEO14
	Isostatic rebound	A 2.38	GEO10, GEO11, GEO13
	Faulting	A 2.24, S 036, J 4.2.06, H 2.1.7	GEO10, GEO11, GEO13, GEO14
Climate change – human-induced	Human-induced climate change	K 11.09, N 2.4.9, H 3.1.1, J 6.08	GEO10, GEO11, GEO13
	Greenhouse effect	K 10.10, A 2.31, A 3.059, W 3.047	GEO10, GEO11, GEO13
	Global effects	A 1.39	GEO10, GEO11, GEO13, GEO14
	Future biosphere conditions	K 8.02	GEO10, GEO11, GEO13, GEO14
Initial defects	Backfill material deficiencies	J 3.2.11	REP6, REP8, REP9, GEO5
	Poor emplacement of buffer	K 3.23	REP8
	Inadequate backfill or compaction, voidage	N 2.2.2	REP6, REP8, REP9, GEO5
	Material defects	N 2.1.6	REP1, REP2, REP4, REP5, REP7
	Organics/contamination of bentonite	K 3.24	REP8, REP10, REP16
	Stray materials left	J 5.03	REP6, REP7, REP8, REP9, REP10, REP16
	Decontamination materials left	J 5.04	REP1, REP2, REP3, REP10, REP16
	Inadvertent inclusion of undesirable materials	N 2.2.4	REP1, REP2, REP3, REP16, REP16
Tectonics	Earthquakes	A 1.29, A 2.21, A 3.045, J 5.15	GEO14
	Fault movement	W 1.011, K 9.03, K 9.04, K 9.01, K 9.02	GEO14
	Faulting	A 2.24, S 036, J 4.2.06, H 2.1.7, W 1.010	GEO14
	Mechanical failure of repository	J 4.2.01	GEO14
	Regional tectonic activity	H 2.1.1, W 1.004, J 6.14, W 1.003	GEO14
	Seismic activity	K 9.05, W 1.012, N 1.2.8, H 2.1.6	GEO14
	Hydrological response to earthquakes	W 1.031	GEO14
	Stress changes – hydrogeological effects	K 9.06	GEO14
Human actions	Accidental intrusion – drilling and pumping	H 5.2.4, A 3.071	REP11, REP16, GEO11, GEO16
	Exploratory drilling	K 11.01, A 2.05, J 5.21, W 3.032	REP11, REP16, GEO11, GEO16
	Geothermal energy production	J 5.34, W 3.007, N 2.3.5, K 11.03	REP11, REP16, GEO11, GEO16
	Reuse of boreholes	J 5.36, A 2.03	REP11, REP16, GEO11, GEO16
	Heat storage in lakes or underground	A 3.061	REP11, REP16, GEO11, GEO16
	Blowouts	W 3.023	REP16
	Cavings	W 2.085	REP16
	Cuttings	W 2.084	REP16
	Drilling fluid flow	W 3.021, W 3.022, W 3.024	REP10, GEO10
	Drilling-induced geochemical changes		
	Fluid injection-induced geochemical changes	W 3.030	REP10, GEO10
	Liquid waste disposal	W 3.010, W 3.027, K 11.04	REP10, GEO10

Table 3-3. EFEPs judged to be important in the selection of the residual scenarios /from Gordon et al. 2008/.

	EFEP	Number in NEA database
Initial defects	Unsealed repository	J 5.02
	Abandonment of unsealed repository	N 2.2.9
	Incomplete closure	A 1.45
	Vault closure (incomplete)	A 2.70
	Unsealed boreholes and/or shafts	J 5.09
	Open boreholes	A 2.47
Human actions	Accidental intrusion – tunnelling	H 5.2.4, A 3.071
	Archaeological investigation	N 2.3.9, W 3.017, J 5.37, W 3.006
	Construction of underground facilities	W 3.016, N 2.3.8, A 2.46, K 11.02, J 5.33, N 2.3.6, A 2.61
	Intrusion (mines)	A 2.37, W 3.018, A 2.46, K 11.02, J 5.33, N 2.3.6, A 2.61
	Other future uses of crystalline rock	J 5.35
	Other resources	W 3.008, W 3.014
Others	Deviant waste package	K 1.27
	Flow through undetected boreholes	W 3.033

3.4 Information flow diagram as a basis for quantitative analyses

Interaction matrices cannot be used directly to perform quantitative analyses. Different models are used to predict repository evolution. The interaction matrices show that changes in one part of the repository can affect the evolution of other parts. The model analyses are therefore linked in chains where the results of one analysis, for example concrete degradation, are used as input in another analysis, for example radionuclide transport. The calculations that are performed and the information flow between them are illustrated in information flow diagrams.

Via information flow diagrams it is possible to check how processes and interactions judged to be important in the interaction matrices are dealt with in the quantitative analysis. The diagrams also define the basic data flows in the analysis and are therefore an important starting point for obtaining input data for different analyses.

Four information flow diagrams were produced in the SAFE project /SKB 2001b/, one for each subsystem and an overall diagram for the whole system. In order to take into account the extended time perspective in this analysis, i.e. up until 100,000 years after closure, these four diagrams have been revised. Note that the content of the information flow, e.g. numerical values, is altered in large parts of the system compared with SAFE, but that other changes, e.g. new information flows, are few. The overall diagram shows the external conditions that are greatly affected by the extended time perspective. Figure 3-3 shows the updated overall information flow diagram for the whole system. In order to clearly show the additional information flow resulting from the extended time perspective, the additions are shown in blue.

Extensive modelling of climate-related changes has been carried out in SR-Can /SKB 2006d/. The modelling of the climate-related changes was based on reconstructed conditions for the past 120,000 years, encompassing the Weichselian glacial cycle and the Holocene interglacial. The modellings cover permafrost evolution, ice sheet evolution and shoreline evolution. A temperature curve developed from measurements of ice cores from the Greenland ice sheet was used to calculate the extent of the ice sheet. The results show the advance and retreat of the ice sheet. Based on the calculated ice thickness, the increased pressure can be calculated.

The future shoreline displacement is modelled on the basis of the position of the Earth's crust and the change in sea level resulting from the build-up and melting of the ice sheet. The modelling of permafrost evolution utilizes the results of the modelling of ice sheet evolution and sea level evolution. Site-specific information on the thermal properties of the bedrock and the geothermic heat flow is used in the modelling. The results of the calculations also show the temperature evolution in the bedrock. In SAR-08, the climate-related changes were based on the modelling done for SR-Can. The information flow diagram has therefore been simplified by placing the whole modelling for the climate-related changes in one calculation/analysis box. Since this box includes analyses for the entire system, information flows directly to the different subsystems. An example of this is temperature evolution, which includes the evolution in both the biosphere and the geosphere and thereby also the heat exchange between them. The resultant temperature evolution is therefore presented in the diagram (Figure 3-3) as information directly to analyses in the three subsystems. The information flow diagram has also been augmented with data on boreholes including location and abstracted water quantity as input data to the local hydrological calculations.

The three detailed diagrams for the subsystems are affected to a lesser extent by the longer time perspective.

The following must be taken into consideration for the biosphere:

- the temperature as information for analysis of the surface hydrology of the sea,
- the temperature as information for analysis of the hydrology in the Quaternary soil layers,
- boundary conditions from the local hydrology in the geosphere as information for analysis of the surface hydrology of the sea,
- the temperature as information for selection of ecosystems,
- given data on possible boreholes with location and abstracted water quantity as input data for calculation of dose.

The following must be taken into consideration for the geosphere:

- the temperature as information for analysis of the local hydrology,
- given data on possible boreholes with location and abstracted water quantity as input data for the local hydrological calculations.
- pressure changes resulting from the advance and retreat of the ice cap for analysis of stress changes that can affect the occurrence and properties of fractures.

The following must be taken into consideration for the repository system:

- the temperature as information for analysis of the changes in waste and barriers,
- pressure changes resulting from the advance and retreat of the ice cap for analysis of the changes in waste and barriers,
- the information on water flow, which also needs to be linked to the analysis of the changes in waste and barriers.

The three detailed information flow diagrams have not been updated; they can be found in the SAFE project's scenario report /SKB 2001b/.

The quantitative description of the input data that have been identified in the information flow diagrams is presented for the most part in the chapter on the initial state, Chapter 4, in the data report for the SAFE project /SKB 2001c/ and together with the presentation of analyses in Chapters 6 and 8.

As a rule, the information flow entails some type of interpretation. The results of an underlying calculation require analysis before they can be used as input for the next step in the computational chain. Underlying calculations and analyses of the results are presented in the description of the reference evolution in Chapter 6. Calculations of radionuclide transport and dose are presented in Chapter 8, and the results of these calculations are presented in Chapter 9.

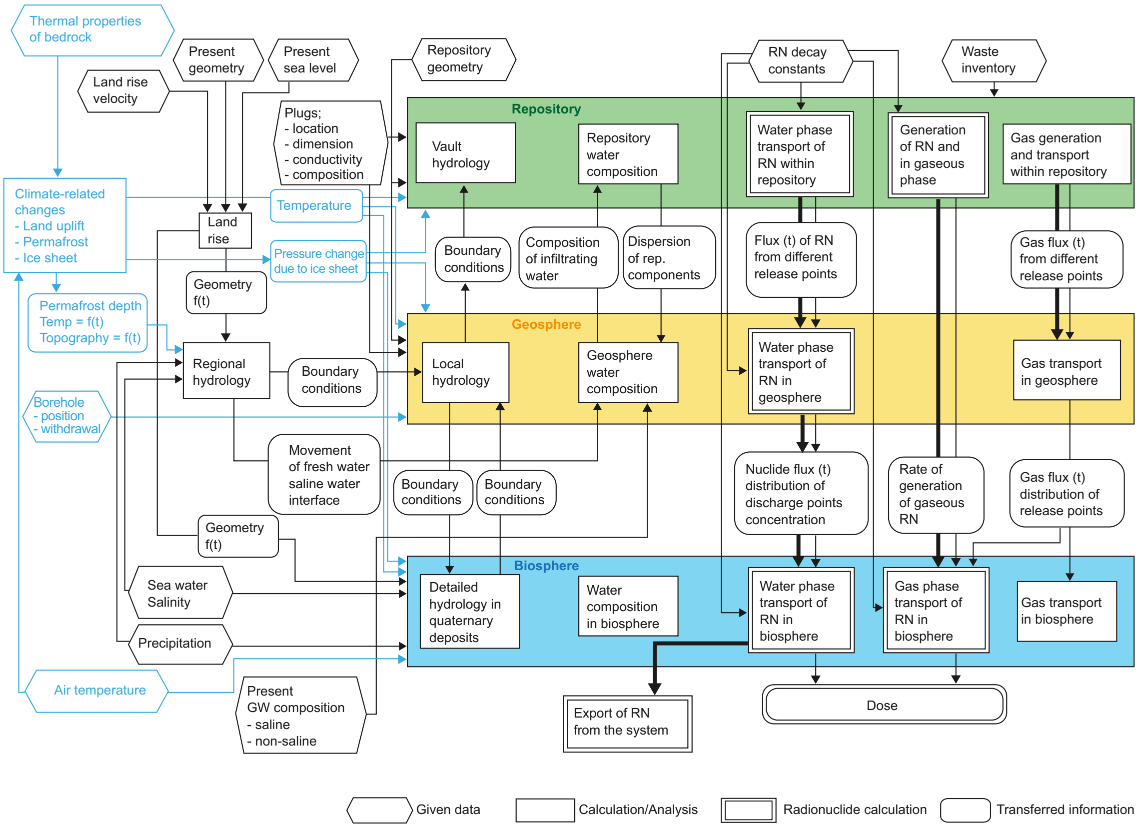


Figure 3-3. *Information flow diagram for calculations/analyses of repository evolution. In order to clearly show the additional information flow resulting from the extended time perspective, the additions are shown in blue.*

4 Initial state in the repository and its environs

4.1 Introduction

This chapter is divided into two parts. The first part describes the actual repository and the second part the environs surrounding the repository. The initial state of the repository and its environs at closure in 2040 is the point of departure for the analysis of the repository's long-term performance. The state of the repository is described in terms of the design of the engineered parts of the repository, the distribution and quantities of different waste types, and their structure.

It is assumed that the environs of the repository at closure in 2040 look like they do today, except for the displacement of the shoreline, due to the fact that the area will have risen about 20 centimetres above the present sea level. The climate, the biosphere and the geosphere in the initial state are described along with uncertainties, if any.

Since SFR 1 is an existing plant (see Figure 4-1), the description of the initial state can in most respects be both accurate and verifiable, but in some respects it must be based on assumptions. The uncertainties in these assumptions are mainly associated with waste quantities in the repository, the nuclide inventory and closure measures. For example, the description of future waste quantities is based on a forecast; the technical solutions that will be used at closure have not yet been finalized; the description of the properties of the rock is based on an interpolation of measurement results from a limited number of boreholes, and so on. Certain conditions change rapidly, for example the system will begin to become saturated with water as soon as pumping ceases. Other conditions, such as the permeability of the rock, can be expected to retain their initial values over long periods, with small variations.

The information and the assumptions that serve as a basis for the initial state are presented in General Part 1, "Facility design and operation", Chapter 2, "Site", and Chapter 5, "Description of facility and function". A lot of information is taken from the previous safety analysis report, and information from the site investigations for the repository for spent nuclear fuel has been used wherever possible.

Figure 4-1. *Geographic location of SFR 1.*

4.2 Design and closure of the repository

The repository is a hard rock facility located about 60 meter beneath the sea. It is reached via access tunnels from a surface facility. The repository is divided into a number of units designed to meet special requirements for different types of waste, see Figure 4-2. SFR 1 is designed with different repository parts intended for waste with different activity levels and for different packaging types /SSR system 130/. The following repository parts are included:

- Silo – for intermediate-level, solidified waste /SSR system 140/.
- BMA – for intermediate-level, mostly solidified waste /SSR system 138/.
- 1BTF and 2BTF – for dewatered ion exchange resin and drums of ashes from trash incineration /SSR system 136/.
- BLA – for low-level solid waste such as trash and scrap /SSR system 137/.

All repository parts are located at the same depth beneath the sea. The bottom of the silo reaches down another 35 metres or so in the rock.

The waste deposited in SFR 1 is short-lived and comes mainly from operation and maintenance of nuclear reactors and from interim storage of spent nuclear fuel. The waste consists primarily of spent organic ion exchange resins from cleaning of reactor water and waste in the form of trash, scrap and mechanical components from maintenance work, etc. A smaller quantity consists of similar waste from other industrial and medical activities and research.

The capacity of the facility is about 63,000 m^3 and the total volume of excavated rock is about 400,000 m^3. This chapter provides a brief description of each repository part. A more detailed description is provided in General Part 1, "Facility design and operation", Chapter 5, "Description of facility and function".

Closure measures have been planned since the design of the facility. Some such measures are carried out during the operating period, for example closure of boreholes and filled disposal chambers. One example of closure of a tunnel is described in this chapter to provide sufficient background material for carrying out the analyses of the repository's long-term performance. Complete sealing and closure of the facility is assumed to take place after all waste has been deposited.

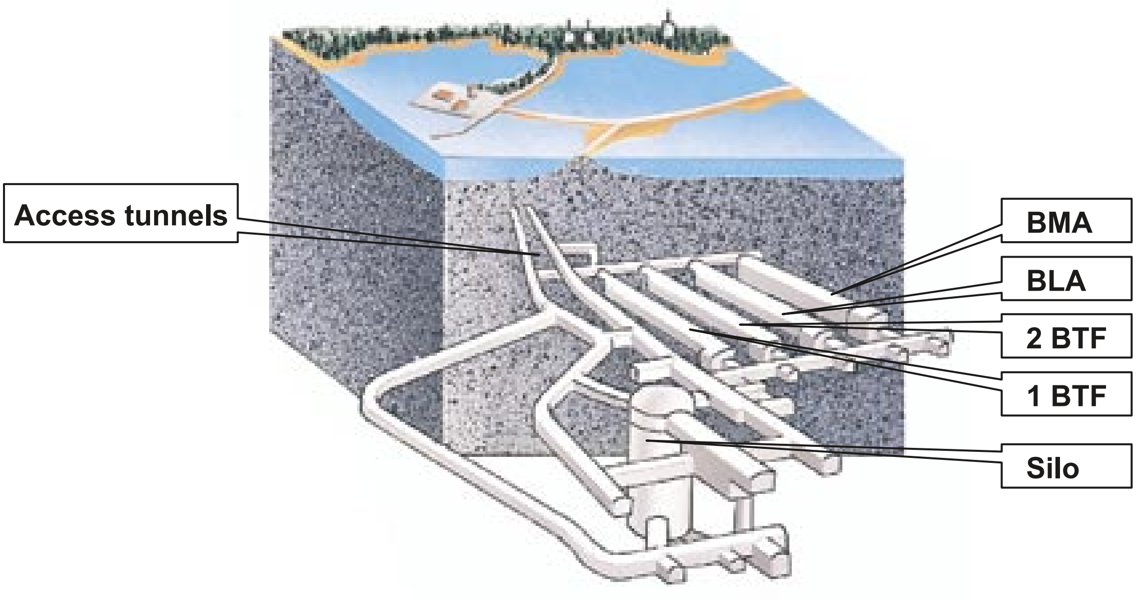


Figure 4-2. *General plan of SFR 1.*

In the planning of closure measures, the possible future construction of repository parts for short-lived decommissioning waste must also be taken into account. Great freedom of choice exists with regard to the detailed design of the closure measures.

4.2.1 Silo

The repository consists of a cylindrical rock cavern in which a free-standing concrete cylinder has been erected. The silo is constructed of in-situ cast concrete and is founded on a bed of sand and bentonite.

The silo contains most of the activity in SFR 1 (about 80%) and therefore has the most extensive barriers. The innermost barriers are in the actual waste package and consist of the waste matrix and the waste container (the packaging). The waste container is embedded in concrete which, together with the compartment walls and the silo walls of reinforced concrete, constitute additional barriers. During the post-closure phase, the silo walls are completely surrounded by bentonite, which thereby constitutes a barrier between the silo and the rock. The outermost barrier is the surrounding rock mass. The rock itself is covered with shotcrete, and there is a rock drainage system for groundwater between the rock and the bentonite. The bottom part of the silo consists of a reinforced concrete pad resting on a layer of sand mixed with bentonite /SSR system 130, SSR system 140/.

Bentonite

The silo in SFR 1 is surrounded by a bentonite buffer, between the reinforced concrete and the rock. The product name of the bentonite is GEKO/QI, and it is a sodium montmorillonite.

The maximum dry density during bentonite application has been estimated to be 1.12 t/m^3 at the bottom and 0.95 t/m^3 at the top of the wall gap by the silo. The silo's bottom bed, which consists of a mixture of sand/bentonite in the proportions 10/90 has been estimated to have a dry density of at least 2.1 ton/m^3 /Pusch 1985/.

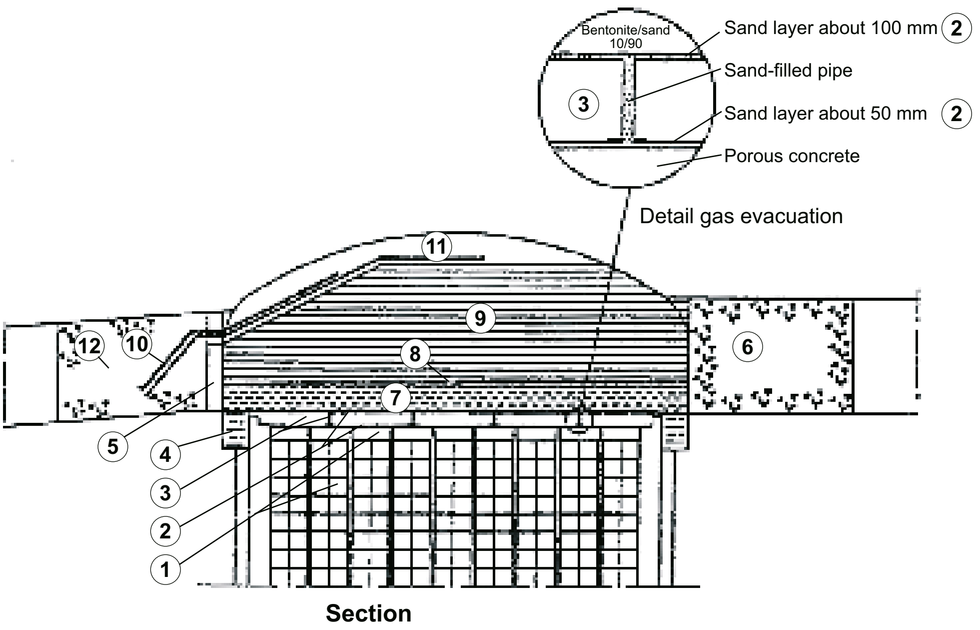
Closure

After each shaft in the silo is filled with waste packages, which are embedded in porous cement mortar after they are loaded in, they are overcast by remote control with a cement overpack all the way up to the top rim of the silo. This provides a radiation shield on top of the silo, which simplifies the work of reinforcing and casting a concrete lid when the silo is full. The concrete lid, which replaces the concrete plugs used during the filling phase, is cast on a thin layer of sand. According to the plans, the lid will also be penetrated by sand-filled gas evacuation pipes so that any gas formed in the silo can escape, see Figure 4-3. The buffer that will completely surround the concrete silo is completed by depositing a mixture of sand/bentonite on top of a thin layer of sand and compacting it. The space above the bentonite mixture is then filled with e.g. cement-stabilized sand /SKB 1999c/.

The upper bentonite layer in the gap between rock and concrete silo is removed and replaced with new bentonite at closure. The reason for this is that the upper bentonite layer swells without confining pressure, which means that the swelling pressure and thereby the density will be low and the hydraulic properties poor.

Both the loading-in tunnel and the silo roof tunnel are fitted with concrete plugs. At closure of the silo, the silo drainage tunnel is also filled with concrete and the silo bottom tunnel's concrete plug is supplemented with backfill of e.g. till and shot rock /SKB 1999c/.

Figures 4-3, 4-4 and 4-5 show closure measures for the silo as described above. The closure measures are to be regarded as examples, however. The final manner of execution will be determined just prior to closure.



1 Grouted waste packages
2 Pressure-distributing sand layer
3 Reinforced concrete pad with gas evacuation pipes
4 Compacted fill of bentonite/sand 30/70
5 Compaction support of concrete
6 Concrete plug
7 Compacted fill of bentonite/sand 10/90
8 Unreinforced concrete pad
9 Compacted fill (friction material)
10 Pipe system for loading-in of sand in silo cupola
11 Cement-stabilized sand
12 Concrete plug – Cast after sand filling

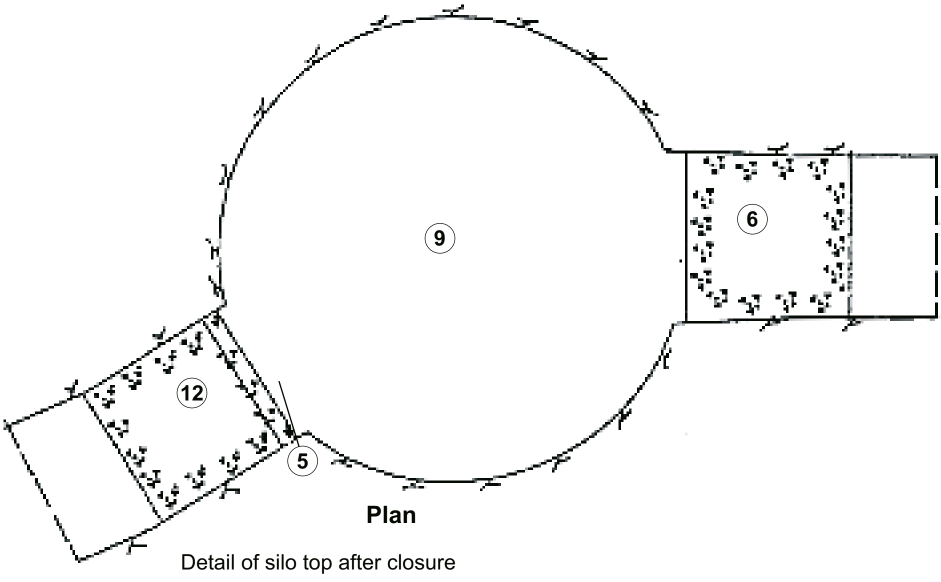


Figure 4-3. *Example of closure of silo, upper part (cupola) /SSR system 192/.*

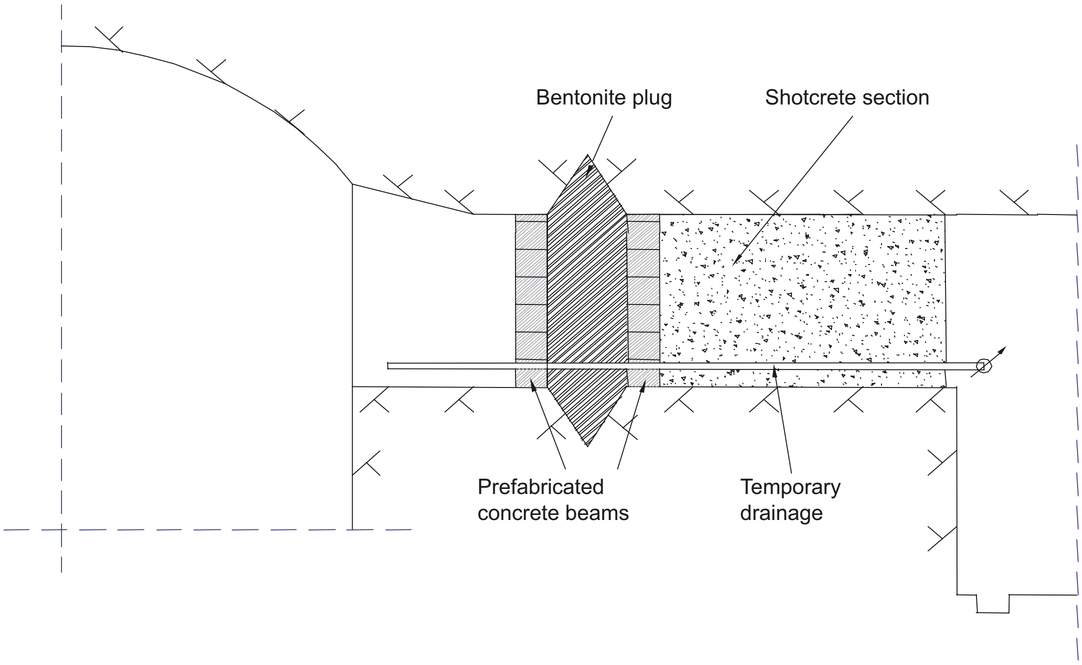


Figure 4-4. *Example of plugging of waste deposition tunnel for silo and rock vaults /Gunnarsson 2005/.*

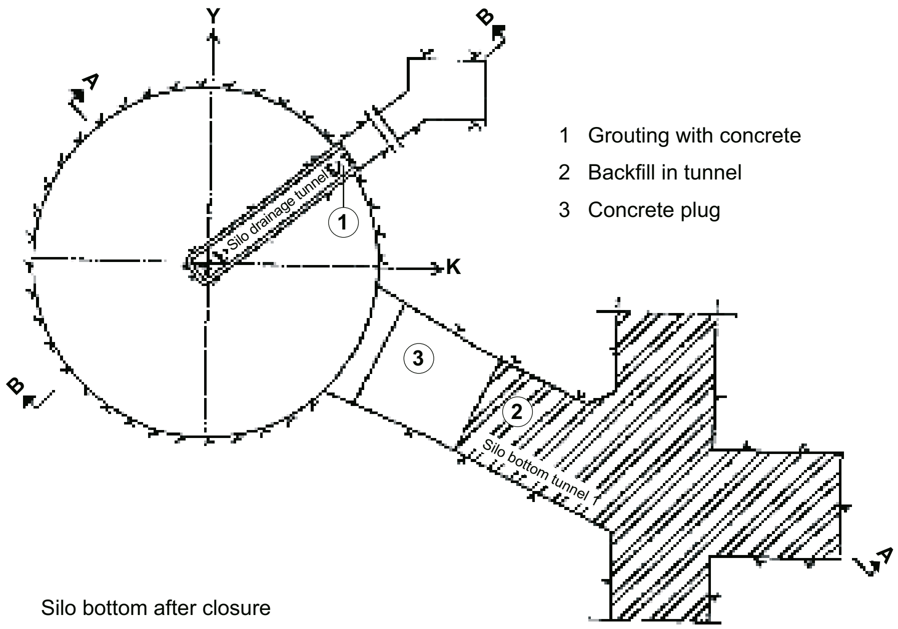


Figure 4-5. *Example of closure of silo, bottom part.*

4.2.2 Rock vault for intermediate-level waste, BMA

The rock vault for intermediate-level waste contains much less activity than the silo, approximately 20% of the total in SFR 1. The packages consist mainly of moulds or drums, see Figure 4-10, and the repository consists of a number of storage compartments /SSR system 138/.

The building's loadbearing structural parts are founded on solid rock. The bottom slab is founded on a base of shot rock levelled with gravel. The bottom slab, walls and floor structures are made of in-situ cast reinforced concrete. The walls and roof of the rock vault are lined with shotcrete /SSR system 130, SSR system 138/.

A prefabricated concrete lid is put in place after the compartments are filled with waste. The lids provide radiation shielding and fire protection. Another concrete layer is cast on top of the prefabricated lids to give the structure added stability and tightness.

BMA has three barriers. The innermost barrier consists of the waste package. Then come the compartments in BMA and finally the surrounding rock.

Closure of BMA

As soon as a compartment in BMA is full, it is closed with a concrete lid and concrete is poured over the lid, see Figure 4-6. It is also possible to backfill the compartments in BMA with e.g. concrete. The closure measures planned for BMA entail that the rock cavern outside the concrete structure is backfilled.

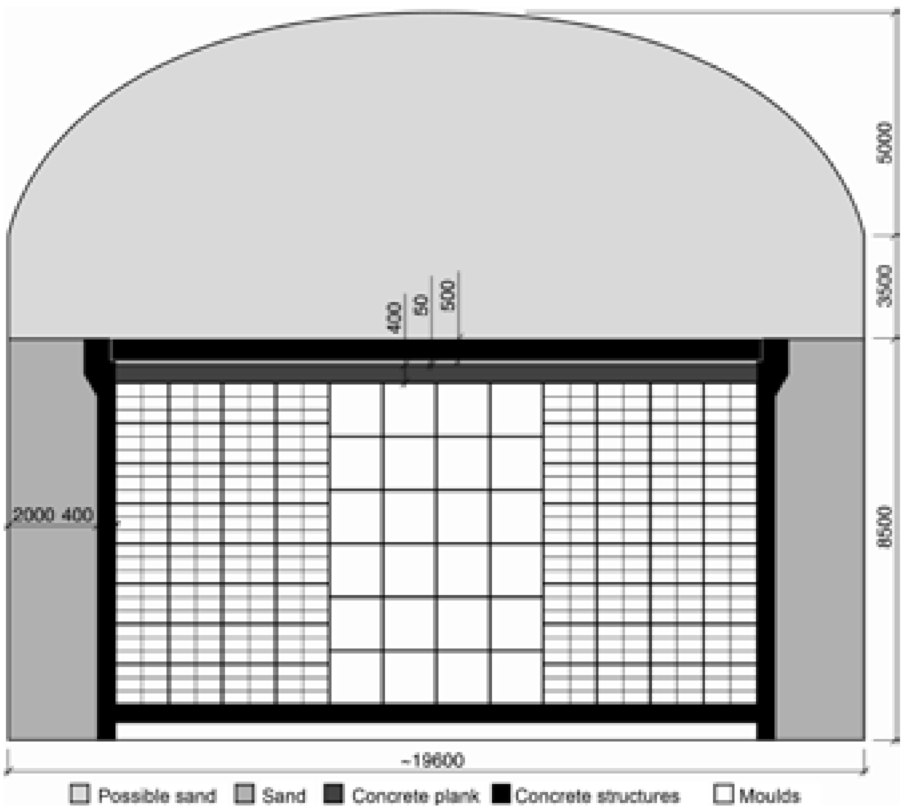


Figure 4-6. *Cross-section of BMA. Gravel may be used instead of sand as a backfill material. Gravel and sand are judged to be equivalent backfill materials and provide the same water flow through the waste.*

When BMA is full and ready for closure, machines and other equipment are removed. A concrete plug is cast against the rock vault tunnel, after which the rock vault is filled with gravel from the transverse tunnel at the other end. Gravel or sand is filled into the loading-in part, the longitudinal control aisles to support the concrete walls, and as backfill of the top. When this filling work is finished, concrete plugs are cast against the tunnel junctions on either short side (Figures 4-4 and 4-8). These plugs are about 5 m thick, and their purpose is to prevent water flow via the tunnel system and direct contact between different rock vaults. A support fill of e.g. till and shot rock is placed on the outside of the plugs /SKB 1999c/.

4.2.3 1BTF and 2BTF

The concrete tank repositories have been designed primarily for storing concrete tanks and drums with very low activity /SSR system 136/, see Figure 4-10.

The concrete tank repositories have a concrete floor, and rock walls and roofs are lined with shotcrete /SSR system 130/. The waste containers in the concrete tank repositories are grouted with concrete /SSR system 136/.

The concrete walls in the actual waste package and the surrounding rock constitute barriers.

Closure of BTF

The closure measures planned for BTF entail backfilling of BTF. In BTF, concrete plugs are cast against the rock vault tunnel, the concrete grout around the waste containers is supplemented so that the concrete tank repositories are filled up above the waste packages and a porous backfill is emplaced at the walls, see Figure 4-7. The top of the concrete tank repositories is backfilled with sand or gravel. Concrete plugs are then cast against the transverse tunnel /SKB 1999c/. The concrete plugs are cast in the same way as for BMA, see section 4.2.2. for more information.

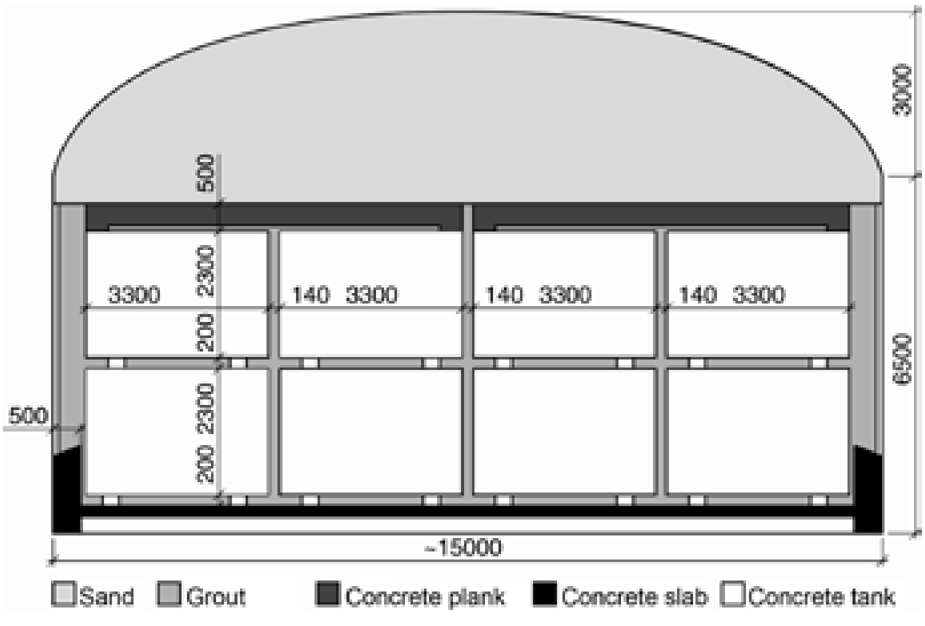


Figure 4-7. Cross-section of BTF.

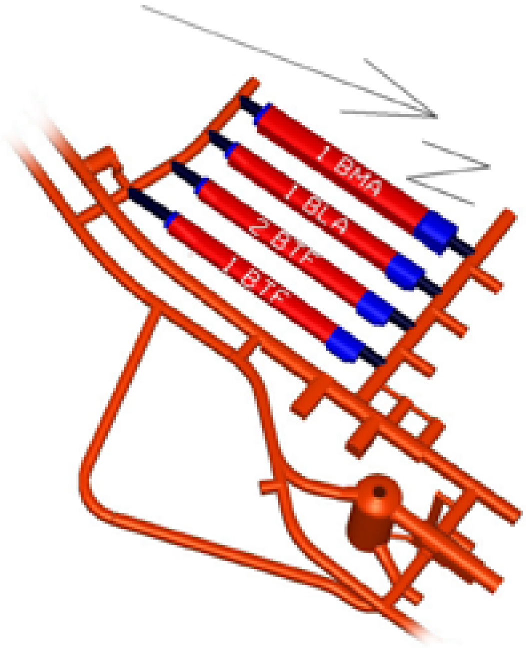


Figure 4-8. *Layout of SFR 1 with the concrete plugs for the rock vaults marked in black. Loading-in and transloading tunnels are marked in blue /Fredriksson 2000/.*

4.2.4 Rock vault for low-level waste, BLA

The rock vault has a concrete floor, and the rock walls and the roof in the rock vault are lined with shotcrete. The waste packages are standard shipping containers, see Figure 4-10.

The BLA barrier consists of the surrounding rock.

Closure of BLA

The closure measures planned for BLA entail leaving the rock vault unfilled.

In BLA, concrete plugs are cast in both ends of the rock vault against the connecting tunnels. No concrete backfill is planned for this chamber /SKB 1999c/.

4.2.5 Closure of access tunnels and boreholes

Closure of the access tunnels, together with closure of the rock vaults, controls the water flow in the disposal chambers in a predetermined manner. Another function of the closure of the access tunnels is to hinder future inadvertent intrusion in the facility.

In the calculations of the long-term performance of the repository, it is assumed that the access tunnels are provided with approximately 100-metre-long plugs between the Singö Zone and the repository area /SKB 1999c/. These plugs are assumed to have the same water permeability as the surrounding rock mass. This can be achieved with concrete, see Figure 4-9. Compacted bentonite could possibly be used as an extra seal against the rock. Experience from the work with the final repository for spent nuclear fuel will prove useful in the closure work.

The planned extension of SFR 1 to accommodate decommissioning waste is taken into consideration when planning the closure of the tunnel system. Final planning of the plugs in the tunnel system is only possible when the total scope of rock vaults and tunnels in the facility is known.

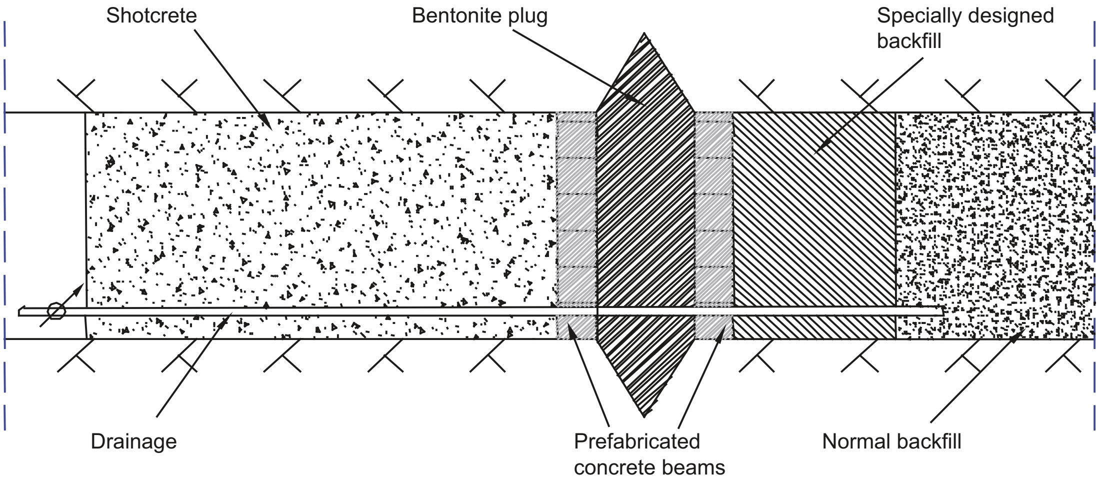


Figure 4-9. *Example of plugging of the access tunnels to SFR 1 /Gunnarsson 2005/.*

The plugs can then be used in combination with hydraulic connections in tunnels, shafts and water-conducting zones to equalize future hydraulic gradients over the disposal chambers. In the present safety assessment, the planned extension of SFR 1 is not taken into consideration.

The boreholes that were included in the preliminary investigations of the rock in the repository area have been closed so that they are no more water-permeable than the rest of the bedrock. This includes holes drilled from the harbour pier and from a platform above the disposal chambers. Sealing and plugging of the boreholes as described in /SKB 1982/ and /SKB 1983/ included the following:

1. Sealing by grouting with cement after drilling to about 40 m below sea level (–40 m).
2. Filling-up with cement to about 38 m below sea level (–38 m).
3. Installation of bentonite-filled, perforated copper tubes to a total length of 10–15 m.
4. Filling-up with cement from the top of the copper tube string up into the casing.

The boreholes that have been drilled from the tunnels during the construction period are closed when they are no longer needed to monitor the groundwater situation in the repository area. Closure will be done according to the same principles as for the boreholes drilled from the ground surface. At the time of repository closure, all boreholes will have been closed.

4.3 The waste in SFR 1

This section about the waste in SFR 1 constitutes a brief summary of the information provided in General Part 1, “Facility design and operation”, Chapter 6, “Radioactive substances and waste in the facility”.

4.3.1 Origin of the waste

Most of the waste in SFR 1 comes from the Swedish nuclear power plants. The source of the radioactive waste is nuclear fission in the reactor core, which gives rise to fission products such as Cs-137 and I-131, but also neutrons. The neutrons in turn create new fission products, but the neutron radiation also activates the uranium in the fuel. As a result of neutron absorption and transformation of the uranium in the fuel, transuranic elements such as are plutonium and americium are formed. Like the fission products, these transuranics are formed in the fuel itself and will only contaminate the reactor water if the fuel cladding is damaged.

However, the largest activity quantities in the reactor water derive from activation of substances outside the fuel rods. These substances may be dissolved or dispersed in the reactor water and come from corrosion of material surfaces, but they may also come from substances on surfaces near the core that are activated directly and then transferred to the reactor water.

The reactor water in the primary circuit undergoes continuous cleanup to remove the radioactive substances. The reactor water is purified in the reactor's cleanup circuits by means of ion exchange resins that absorb radionuclides that occur as ions in the reactor water. The ion exchange resins also remove "crud", dispersed particles consisting of oxides/hydroxide of engineering materials.

Even though most of the radionuclides that have left the core are thus separated in the cleanup system, small amounts will be spread to other systems. Relatively large volumes of ion exchange resins and mechanical filter resins are used in the boiling water reactors for cleanup of the water that condenses in the condenser. Due to the fact that small quantities of radioactive substances are carried from the reactor to the turbines, this water and its filter resins become weakly radioactive.

Additional waste consisting of ion exchange resin, mechanical filter resin and precipitation sludge arises in the water cleanup system.

Some radioactive substances have also been released from the spent fuel stored in the storage pools at the nuclear power plants and at Clab. These pools also have cleanup systems with ion exchange resins that are used in roughly the same way as in the reactor water cleanup systems.

Solid waste is also generated at nuclear facilities. Compared to the wet waste, the volume of the solid waste is usually much greater, but its activity is often much lower. The solid waste consists of components of the primary system or other active systems, but most consists of material that has been brought into a classified area, used, contaminated and discarded.

4.3.2 Material types

Much of the activity in SFR 1 is present in the wet waste. The wet waste consists for the most part of bead resin, powder resin, mechanical filter aids and precipitation sludge. The ion exchange resins consist of organic polymers with acidic or basic groups, making them capable of cation or anion exchange.

A large portion of the waste volume in SFR 1 consists of metals, above all carbon steel and stainless steel. Scrap metal arises mainly during maintenance outages when equipment is discarded, modified or renovated.

The largest volume of raw waste consists of combustible solid waste. As a result of incineration in Studsvik or local at-plant disposal, the volume remaining for disposal in SFR 1 is comparatively small, however. The waste consists mainly of cellulose (paper, cotton and wood) and plastics (e.g. polystyrene, PVC, polyethylene, polypropylene, etc).

Other materials occurring in the waste include mineral wool (used for insulation), concrete and brick. Various additional materials are also included in smaller quantities.

4.3.3 Waste packaging

Waste to SFR 1 is mainly packaged in the following containers:

- Concrete moulds (with cement-solidified ion exchange resins, filter aids and evaporator concentrate as well as concrete-stabilized trash and scrap metal).
- Steel moulds (with cement- or bitumen-solidified ion exchange resins or concrete-stabilized trash and scrap metal).
- Steel drums (with cement-stabilized ash drums).
- Standard containers (mainly with trash and scrap metal).
- Concrete tanks (with dewatered ion exchange resins).

There may be certain other odd containers, and in some cases large items of waste (components) may be deposited without containers. Figure 4-10 shows the different waste containers. For more detailed information about the different packaging types, see General Part 1, "Facility design and operation", Chapter 6, "Radioactive substances and waste in the facility".

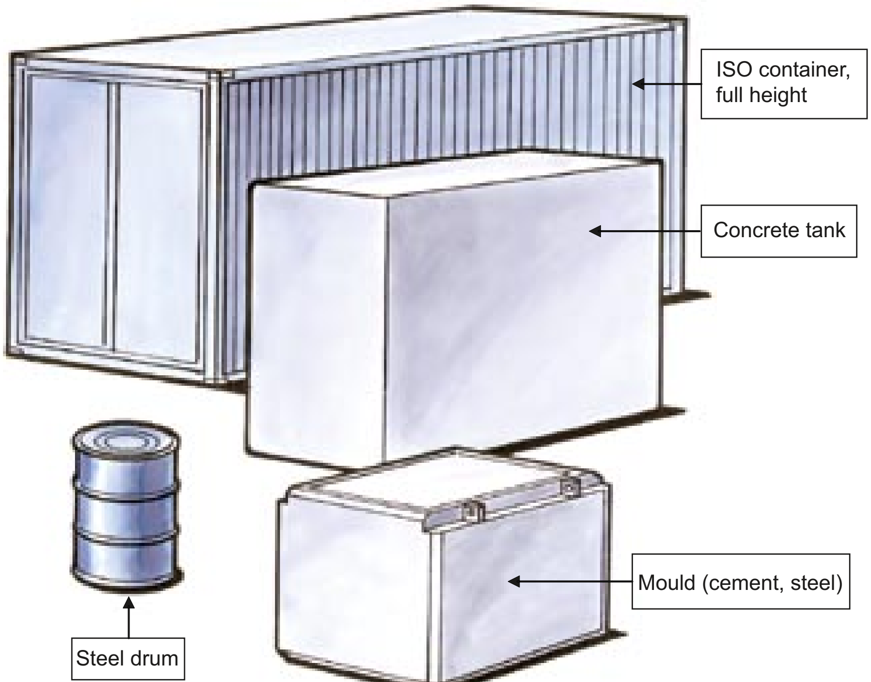


Figure 4-10. *Waste containers in SFR 1.*

4.4 Material quantities and activity content in different parts of the repository

Material quantities for the silo and the other rock vaults in SFR 1 are presented in this section. The material quantities are taken from /Almkvist and Gordon 2007/. The amount of activity in SFR 1 is presented in Chapter 8.

4.4.1 Waste in the silo

Table 4-1 shows the quantities of materials expected to be present in 2040 /Almkvist and Gordon 2007/. Materials and quantities in the table include the waste itself, conditioning materials and packaging (containers).

4.4.2 Waste in BMA

Table 4-2 shows the quantities of materials expected to be present in 2040 /Almkvist and Gordon 2007/. Materials and quantities in the table include the waste itself, conditioning materials and packaging (containers).

Table 4-1. Material quantities in the silo repository.

Material	Weight (kg) 50 years' operation	Area (m^2) * 50 years' operation
Iron/steel	2.79E+06	1.22E+05
Aluminium/zinc	4.02E+02	7.60E+01
Cellulose (wood, paper, cloth)	5.57E+03	
Other inorganic	1.91E+04	
Other organic (plastics, rubber, cable)	3.22E+04	
Ion exchange resins	1.80E+06	
Sludge	2.00E+04	
Bitumen	1.04E+06	
Cement and concrete	1.56E+07	

* "Area" means the area exposed to groundwater and thereby to corrosion after closure of SFR 1.

Table 4-2. Material quantities in BMA.

Material	Weight (kg) 50 years' operation	Area (m^2) * 50 years' operation
Iron/steel	2.68E+06	1.24E+05
Aluminium/zinc	7.09E+03	1.02E+03
Cellulose (wood, paper, cloth)	1.44E+05	
Other inorganic	3.43E+04	
Other organic (plastics, rubber, cable)	2.85E+05	
Ion exchange resins	1.63E+06	
Sludge	5.86E+04	
Evaporator concentrate	6.20E+05	
Bitumen	1.76E+06	
Cement and concrete	1.25E+07	

* "Area" means the area exposed to groundwater and thereby to corrosion after closure of SFR.

4.4.3 Waste 1BTF

Table 4-3 shows the quantities of materials expected to be present in 2040 /Almkvist and Gordon 2007/. Materials and quantities in the table include the waste itself, conditioning materials and packaging (containers).

4.4.4 Waste in 2BTF

Table 4-4 shows the quantities of materials expected to be present in 2040 /Almkvist and Gordon 2007/. Materials and quantities in the table include the waste itself, conditioning materials and packaging (containers).

4.4.5 Waste in BLA

Table 4-5 shows the quantities of materials expected to be present in 2040 /Almkvist and Gordon 2007/. Materials and quantities in the table include the waste itself, conditioning materials and packaging (containers).

Table 4-3. Material quantities in 1BTF.

Material	Weight (kg) 50 years' operation	Area (m^2) * 50 years' operation
Iron/steel	4.20E+05	4.54E+04
Aluminium/zinc	3.00E+04	1.19E+04
Ashes	1.48E+05	
Cellulose (wood, paper, cloth)	1.68E+03	
Other organic (plastics, rubber, cable)	1.31E+04	
Other inorganic	4.65E+03	
Ion exchange resins	1.77E+05	
Sludge	9.31E+03	
Cement and concrete	1.98E+06	

* "Area" means the area exposed to groundwater and thereby to corrosion after closure of SFR.

Table 4-4. Material quantities in 2BTF.

Material	Weight (kg) 50 years' operation	Area (m^2) * 50 years' operation
Iron/steel	6.39E+05	3.72E+04
Aluminium/zinc	2.59E+03	1.44E+03
Ashes	2.53E+04	
Cellulose (wood, paper, cloth)	1.66E+02	
Other organic (plastics, rubber, cable)	6.03E+04	
Other inorganic	4.65E+03	
Ion exchange resins	8.11E+05	
Sludge	4.38E+04	
Cement and concrete	3.75E+06	

* "Area" means the area exposed to groundwater and thereby to corrosion after closure of SFR.

Table 4-5. Material quantities in BLA.

Material	Weight (kg) 50 years' operation	Area (m^2) * 50 years' operation
Iron/steel	3.78E+06	2.20E+05
Aluminium/zinc	5.58E+04	8.36E+03
Cellulose (wood, paper, cloth)	4.33E+05	
Other organic (plastics, rubber, cable)	1.48E+06	
Other inorganic	1.05E+05	
Ion exchange resins	9.77E+04	
Bitumen	1.17E+05	
Cement and concrete		

* "Area" means the area exposed to groundwater and thereby to corrosion after closure of SFR.

4.5 Integrity and condition of the barriers

The rock vaults in SFR 1 have different engineered barriers. The engineered barriers in the repository retard releases of radionuclides. The engineered barriers in each repository part and the expected condition of the engineered barriers at closure are described below.

4.5.1 Corrosion

Oxygen is available during the operating period, which means that aerobic corrosion can occur /Höglund and Bengtsson 1991/. Corrosion of iron is extensive in the environment, with moisture and oxygen available, that prevails in most of the repository during the operating period. Corrosion is so rapid that it can be expected that containers, steel moulds and certain older drums will be extensively corroded during the operating period. Anaerobic corrosion can occur in parts of the silo where oxygen is not present during the operating phase, see section 4.5.3. There are no requirements with regard to long-term function for containers made of of iron.

Aluminium is covered by a passivating oxide layer, and alkaline conditions cause the oxide to dissolve. Alkaline conditions can only be obtained after groundwater has reacted with concrete. Since the repository is drained by pumping during the operating period, the aluminium waste will be covered by its passivating oxide layer. Corrosion of aluminium is therefore negligible during the operating period, while it is extensive after closure.

4.5.2 Mechanical evolution

Continuous inspection and scaling of any loose rock material from the repository takes place during the operating period. Extra rock bolts and shotcrete are applied where necessary. The rock caverns are therefore expected to be intact at the end of the operating period.

Some cracking of concrete barriers can occur during the operating period. The reason for this may be thermal stresses caused by hydration of the concrete, shrinkage due to the fact that parts of the concrete dry out, or settlement due to movements in underlying material. Cracking is not expected to be extensive, and is to some extent detectable on inspection.

Concrete as well as bentonite barriers are not expected to be affected in a way that would degrade their long-term function of limiting advective transport in the repository.

4.5.3 Silo

Most of the waste in the silo is solidified in concrete or bitumen matrices, which in themselves constitute engineered barriers. In addition the waste is surrounded by the following engineered barriers:

- Waste package
- Grouting concrete and compartment walls
- Concrete silo walls
- Bentonite or sand/bentonite buffer

Condition of the barriers

The waste packages (moulds and drums) in the silo are grouted with (embedded in) concrete. This means that the condition of the waste packages cannot be inspected afterwards. If the waste packages corrode in the silo under anaerobic conditions, hydrogen may be formed. Simulations of corrosion of the waste packages show that the hydrogen concentration in the air will increase /Moreno et al. 2001/.

Other barriers are expected to be in perfect condition at closure in 2040.

Settlement in the silo

Measurements are made regularly of settlement in the silo. The annual reports on measurements of movements in the silo up until 1999 described the background to the prediction of the settlement process and the results of the measurements from the start in 1987. The 1999 report concluded that the settlement process was so slow and predictable that its progress could be checked and reported on at longer intervals than 1 year, for which reason an interval of 3 years was chosen /Hökmark and Pusch 2002/.

Figure 4-11 shows predicted settlement for the cases “unloaded silo” and “load increase by 1,600 tonnes per year”. The actual load increase, including grout, averages about 850 tonnes per year. This means that the temperature effects that are assumed to have had an impact on the movement of the top of the silo have decreased, and that its subsidence was expected to be 15–17 mm in 2002. Actual subsidence has followed the prediction very closely, and from the end of September 1999, i.e. 12 years after completion of the silo, until 1 October 2002 the movements amounted to about 15 mm. By far the biggest contribution to settlement is the compression of the 1.5 m thick bottom bed, but some contribution also comes from the bentonite backfill. The temperature effects are small and cause a slight rise in the silo top /Hökmark and Pusch 2002/.

Settlement in the silo up to 2040 has been estimated by extrapolation of the present curve in Figure 4-11 to be 50 mm.

Subsidence since 1994 has been uniform and diminishing. Actual subsidence has followed the prediction closely and is of the originally estimated order of magnitude /Hökmark and Pusch 2002/.

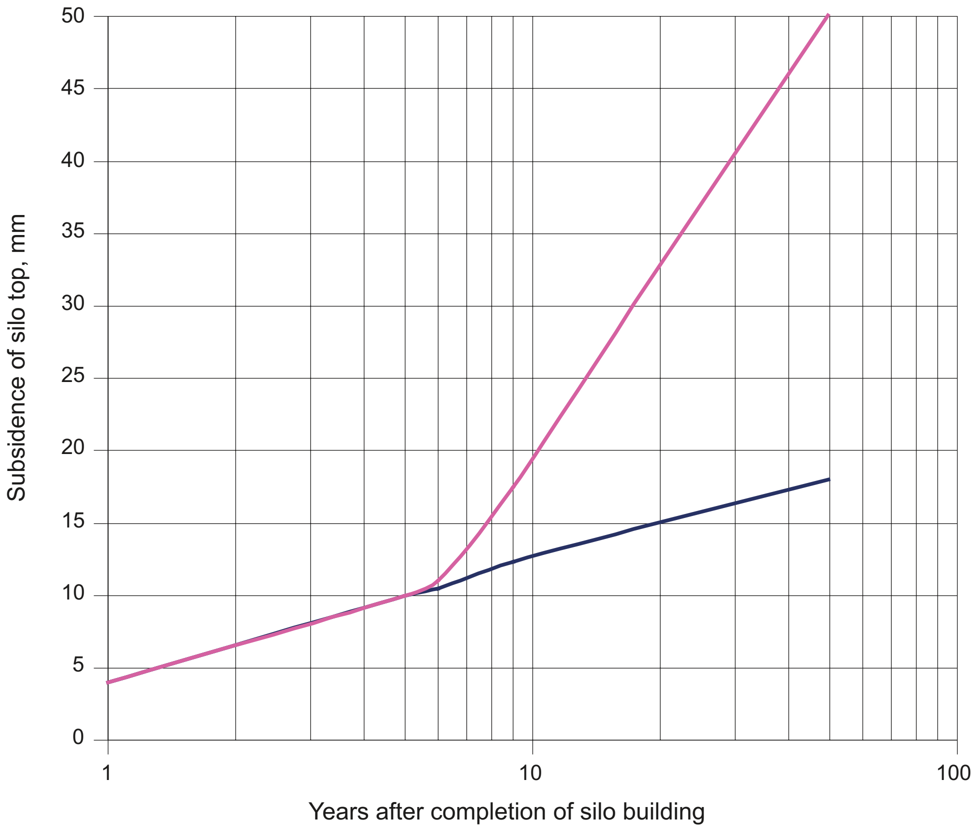


Figure 4-11. Expected and actual movement of the silo top. The upper branch of the curve represents expected subsidence at an average annual load increase of 1,600 tonnes. The lower branch of the curve pertains to an unloaded silo. Year 1 is 1987 /Hökmark and Pusch 2002/.

Vertical movements of the top surface of the bentonite fill

Small vertical movements occur of the top surface of the bentonite fill at the silo. These small movement show that no significant wetting has yet occurred of the bentonite wall fill, which in turn suggests that the wall drainage is functioning as intended /Hökmark and Pusch 2002/.

Pressure build-up in the wall fill

A number of pressure cells for measurement of the swelling pressure in the wall fill are installed at the silo. Pressure gauges are installed at floor level, mid-height level (25 m above the floor) and at silo top level (50 m above the floor). The most recent readings are from 2002 and show roughly the same values as the preceding measurement occasions (1992, 2000 and 2001), see Table 4-6.

At the uppermost measurement level, the values have decreased slightly and are well below the pressure that should have been generated when the fill was applied. At mid-height the gauges show considerably lower values than that corresponding to the silo pressure. The pressures at the bottom of the silo are also much lower than predicted. This indicates more effective dewatering of the surface rock and drainage than had been assumed at the design stage /Hökmark and Pusch 2002/.

Table 4-6. Readings from the pressure build-up in the wall fill /Hökmark and Pusch 2002/. For information on the location of the pressure cells, see /Pusch 2003/.

Cell	Level	Open. pr.*	1992	2000	2001	2002	Comment
G4	Wall-low**	0.130	0.055	0.070	0.065	0.070	Stable
G5	Wall-low	0.140	0.030	0.050	0.050	0.050	Stable
G6	Wall-mid***	0.330	0	0	0	0	No pressure
G7	Wall-mid	0.340	0	0	0	0	No pressure
G8	Wall-high****	0.080	0.045	0.050	0.050	0.030	Slightly diminishing
G9	Wall-high	0.050	0.015	0.035	0.030	0.015	Slightly diminishing

* Pressure required for Glötzl piezometer to open. If the actual pressure is lower it is set as 0. Where pressure values are given they represent the excess pressure above the opening pressure and thereby the actual pressure (difference between measured pressure and opening pressure).

** The gauges are located at silo floor level (silo floor level).

*** The gauges are located at silo mid-height level (25 m above the floor).

**** The gauges are located at silo top level (50 m above the floor).

4.5.4 BMA

In BMA the radioactive waste is stored in concrete compartments that are covered with prefabricated concrete blocks and overcast with concrete. The engineered barriers are the waste packages and the concrete walls.

Condition of the barriers

The waste packages in BMA are made of concrete or steel. The steel waste packages will probably eventually start to rust, while the concrete waste packages are expected to be intact and in perfect condition in 2040, at the closure of SFR 1.

4.5.5 BTF

The waste packages placed in BTF are made of concrete or steel. The walls of the concrete tanks comprise the technical barrier here.

Condition of the barriers

The steel waste packages will probably eventually start to rust, while the concrete waste packages are expected to be intact and in perfect condition in 2040, at the closure of SFR 1.

4.5.6 BLA

ISO containers are placed in BLA, see Figure 4-10. There is no engineered barrier in BLA.

Condition of the barriers

The steel waste packages will probably eventually start to rust.

4.6 Climate

It is assumed that the present-day climate in the Forsmark area will still prevail at the time of closure. The possible impact of the greenhouse effect on the climate in the Forsmark area has not been taken into account for the initial state. For more information on the climate in the Forsmark area, see General Part 1, "Facility design and operation", Chapter 2, "Site". The mean annual temperature in the Forsmark area is about 5.5°C (1961–1990), compared with 5.0°C at the weather stations in Risinge and Films Kyrkby /Johansson et al. 2005/. Virtually all mean annual temperatures since 1988 have been higher than this value.

Due to the geographic location of the Forsmark area on the coast, the amount of precipitation is lower than inland. Two local meteorological stations, Högmasten and Storskäret, in the area around the Forsmark nuclear power plant are used to obtain representative values for e.g. precipitation. In calculating the 30-year mean precipitation for the Forsmark area, the values for SMHI's stations at Östhammar and Risinge were corrected to arrive at values for the stations at Högmasten and Storskäret of 568 and 549 mm, respectively (1961–1990) /Johansson et al. 2008/.

The maximum intensity of the precipitation varies greatly with the duration of the precipitation occasion. It can be very high in connection with brief thundershowers /Johansson et al. 2005/.

The prevailing meteorological conditions in the area affect water currents and thereby water turnover in Öregrundsgrepen (See section 4.7.2).

4.7 Surface ecosystems

Surface ecosystems in Forsmark have been described in connection with the site investigations for the deep repository for spent fuel at Forsmark /Lindborg 2005, SKB 2006b/ and in several studies of the surface ecosystems conducted in the previous SAFE study /Kautsky 2001/. In conjunction with the latter study, knowledge was compiled from previous studies in the area from the construction of the Forsmark NPP and from the Biotest basin. Studies of importance for the present safety assessment include a field survey of the marine environment above the repository /Kautsky et al. 1999/, models of the turnover of materials /Kumblad 1999, 2001, Kumblad and Kautsky 2004/ and water turnover in the marine area /Engqvist and Andrejev 1999/ and of compilations of lakes in the area /Brunberg and Blomqvist 1999, 2000, Brunberg et al. 2004/. The process of land uplift and the sedimentation environment are described in /Brydsten 1999a, 1999b, 2004/. All data presented below and used in the safety assessment are based on published data for the SR-Can safety assessment /SKB 2006a/.

The land area around Forsmark is relatively flat and slopes slightly to the east. Most of the area is less than 20 metres above sea level /Werner et al. 2007/. The highest point has been situated above the highest coastline since the last glaciation. Today's landscape is strongly influenced by ongoing shoreline displacement at a rate of about 6 mm/year /Ekman 1996/. A large portion of the surrounding terrestrial environment has risen above sea level during the past 1,000 years, which means that processes such as chemical weathering and peat formation have been taking place during a relatively short period. The till and glacial clay contain a great deal of calcium carbonate from Ordovician limestone, which occurs frequently on the sea floor north of the Forsmark area /SKB 2006a/.

The properties in surface ecosystems that are most important for the long-term safety assessment are described below.

4.7.1 Population and living habits

There are no permanent residents in the area around Forsmark, covering 19.5 km² around the Forsmark nuclear power plant. There are only five vacation homes in the area and three uninhabited farms, one of which is in use. This farm, specializing in beef cattle, is located at Storskäret and uses the land for grazing and feed production. The predominant cereal crop is barley. The land used for agriculture constitutes only 4% of the total land in the area /Milander et al. 2004/.

The area around Forsmark is utilized for outdoor activities in the form of hunting, fishing and berry and mushroom picking. There is more hunting around Forsmark and in the Östhammar hunting district than in the county as a whole. An average of nearly 1.5 times as many moose have been taken in the parish than in the county as a whole since the 1999/2000 season /Milander et al. 2004/.

The biggest job sector is electricity production. But there is considerable in-commuting of people to the parish during the daytime. Most of them work at Forsmarks Kraftgrupp /Milander et al. 2004/.

There are approximately 20 licensed commercial fishermen in Östhammar Municipality. They are occupied with small-scale coastal fishing for consumption and sell their catch to local buyers /Milander et al. 2004/.

4.7.2 The marine area

Most of the area above SFR 1 is covered by the sea today. The marine area is the southernmost part of the Bothnian Sea and consists of a large open bay, Öregrundsgrepen. The bay opens to the north into largely open sea stretching nearly 400 km. In the southeast there is a long, narrow, shallow strait at Öregrund stretching more than 15 km southward to Singö (Figure 4-12). Since Öregrundsgrepen is exposed to the open sea, the mean retention time of the water is short, about 12 days, except for the deepest water, which has a much longer mean retention time /Engqvist and Andrejev 1999/. A southward current dominates in the strait, but it accounts for only a small portion of the water turnover. The salinity in Öregrundsgrepen is about 3.9‰ in the surface water /Nilsson et al. 2003/. The salinity in the Åland Sea is slightly higher and more stable than in Öregrundsgrepen. During the winter when Öregrundsgrepen can be covered with ice, the salinity of the surface water can go down to less than 1‰ due to the fact that fresh water is accumulated in the ice. The halocline and thermocline in Öregrundsgrepen are weak and temporary and dissolve quickly when the weather changes /Kautsky 2001/.

The coast at the western part of Öregrundsgrepen is flat and shallow, about 5 metres deep at SFR 1, and the sea floor above SFR 1 consists to a great extent of bouldery till with occasional outcrops. In the area above SFR 1, the thickness of the till varies between 4 and 14 metres, while the thickness of the clay varies between 0 and 4 metres. The floor of Öregrundsgrepen is dominated by clay, about 55%. This clay is covered by a thin layer of gyttja, sand, stone and gravel /Lindborg 2005/. Along the eastern part towards Gräsö is a deep area with a depth of 40–60 m. The coast here is steeper and the bottom is dominated by clay and rocks.

The area immediately above SFR 1, about 11 km², which has been used as a model area for study of current and future conditions (Figure 4-12), is very open today and subjected to wave exposure of the same magnitude as the rest of Öregrundsgrepen. The average and maximum depths in the area are around 10 m and 19 m, respectively, see Table 4-7 /Lindborg 2005/. The average age, i.e. the average time an individual water parcel spends in a particular basin from the time of its inflow, is very short, around 0.66 day /SKB 2006b/. The material in the bottom is a wave-washed till with very little fine material /Sigurdsson 1987/, which has also been confirmed by the expanded survey of the sea bottoms in connection with the site investigations /Elhammer and Sandkvist 2005/. The total sedimentation is limited in this area but has prospects of increasing /Brydsten 1999a/.

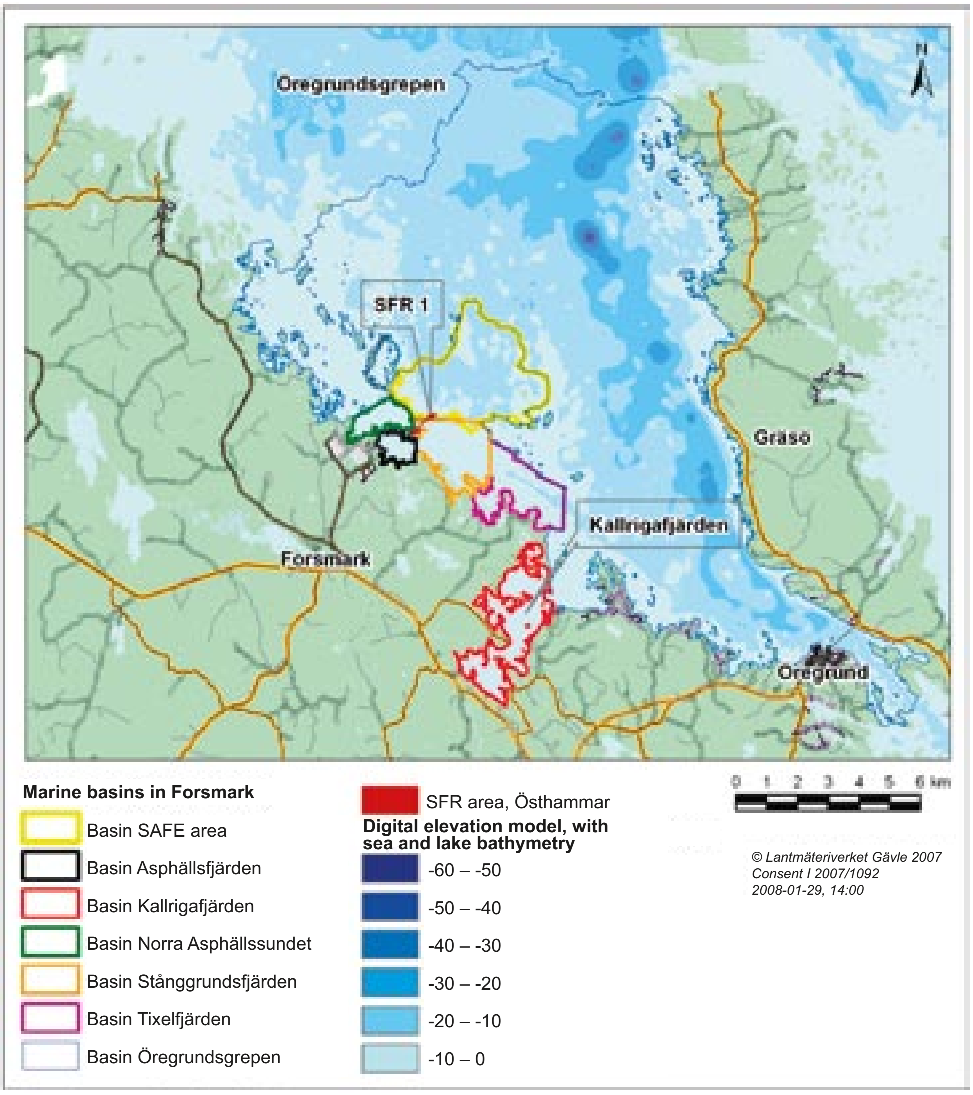


Figure 4-12. *Map of Forsmark and Öregrundsgrepen. Forsmark model area (Basin SAFE area).*

Table 4-7. Oceanographic and morphometric data for the model area at SFR 1 and Öregrundsgrepen.

Parameter	Parameter value	Reference
Model area		
Average depth	10 m	/Lindborg 2005/
Max. depth	19 m	/Lindborg 2005/
Area	11.5 km^2	/Lindborg 2005/
Average age of water	0.66 day	/SKB 2006b/
Öregrundsgrepen		
Average depth	11,2 m	/Kautsky 2001/
Max. depth	60 m	/Engqvist and Andrejev 1999/
Area	456 km^2	/Kautsky 2001/
Average age of water	6.3 days	/SKB 2006b/

The bottoms above SFR 1, which are more or less hard and relatively stable, have a rich fauna and flora that are characteristic of hard bottoms, i.e. algae and sedentary animals. There are large populations of vascular plants on the more fine-grained bottoms (from gravel and finer sediments) in the area. The quantity of plants and animals is of the same order of magnitude as in the Gräsö-Singö area. But in the latter area there is much more bladderwrack (*Fucus vesiclosus*) and blue mussels (*Mytilus edulis*). These two species prefer rocky but also bouldery bottoms, which are less common in the area above the final repository. The very small amounts of blue mussels may also be due to the fact that the area is affected more by Bothnian Sea conditions (above all slightly lower salinity) and Gräsö-Singö than by conditions typical of the Baltic Proper. The moss *Fontinalis dalecarlica* is common in the area, which indicates a strong influence from the Bothnian Sea /Kautsky et al. 1999/.

A marine inventory of the plant and animal communities in different areas in Öregrundsgrepen was undertaken in conjunction with the site investigations. The inventory shows that the plant biomass is dominated by *Vaucheria sp.* and that the snail *Hydrobia sp.* and the Baltic mussel *Macoma baltica* dominated the detrivore biomass /Borgiel 2005/.

The fish fauna has been studied in the area around Forsmark, particularly with respect to possible effects of cooling water discharge, special studies at the Biotest basin, and environmental monitoring at the nuclear power plant. An inventory of the fish population in the Forsmark area was conducted in conjunction with the site investigations. The dominant fish species in terms of share of catch frequency included perch, ruffe, roach and Baltic herring /Heibo and Karås 2005/.

There are periodically large numbers of diving ducks in the area around Forsmark, such as eider, as well as other sea birds such as cormorant, arctic skua, etc. Birds of prey such as osprey and white-tailed eagle are also found there. The number of different bird species recorded during the period 2002–2004 was 96 /Green 2005/.

4.7.3 Terrestrial environs

The vegetation is affected by the bedrock, the Quaternary deposits and human use of the land. The bedrock in Forsmark consists for the most part of granite. The Quaternary deposits consist for the most part of wave-washed till. The till is covered in most cases by forests, which are dominated inland by pine and spruce. But there are quite a few hardwood species as well, such as alder, aspen, ash, rowan, and birch, especially near water /Lindborg 2005/. The till is lime-rich, which means that the undergrowth is luxuriant with rare species such as orchids. In protected locations, the flat shore often results in coastal meadows rich in vegetation that are periodically flooded. In locations exposed to wave action the shore is sometimes boulder-strewn, stony and gently sloping.

In parts of the catchments, lakes and wetlands make up a large portion. The wetlands cover 10%, 12% and 17% of the main catchments Forsmark 1, 2 and 8, respectively. In some of the subcatchments, wetlands comprise between 2% and 3% of the area, see Figure 4-13. Many of the wetlands are often classified as rich or extremely rich fens, due to the lime-rich water flowing through them. These fens are dominated by brown mosses (*Scorpidium scorpioides*) /SKB 2006a/. The vegetation contains many herbaceous plants, such as orchids. On high-lying areas there are peat bogs with sphagnum moss /Lindborg 2005/. In these areas it is also possible to find fens, but they are rare, mainly due to the short time that has passed since the area rose from the sea. The wetlands can be roughly classified into two types: those that accumulate peat and those where there is a high rate of decomposition, thereby minimizing peat formation /SKB 2006a/.

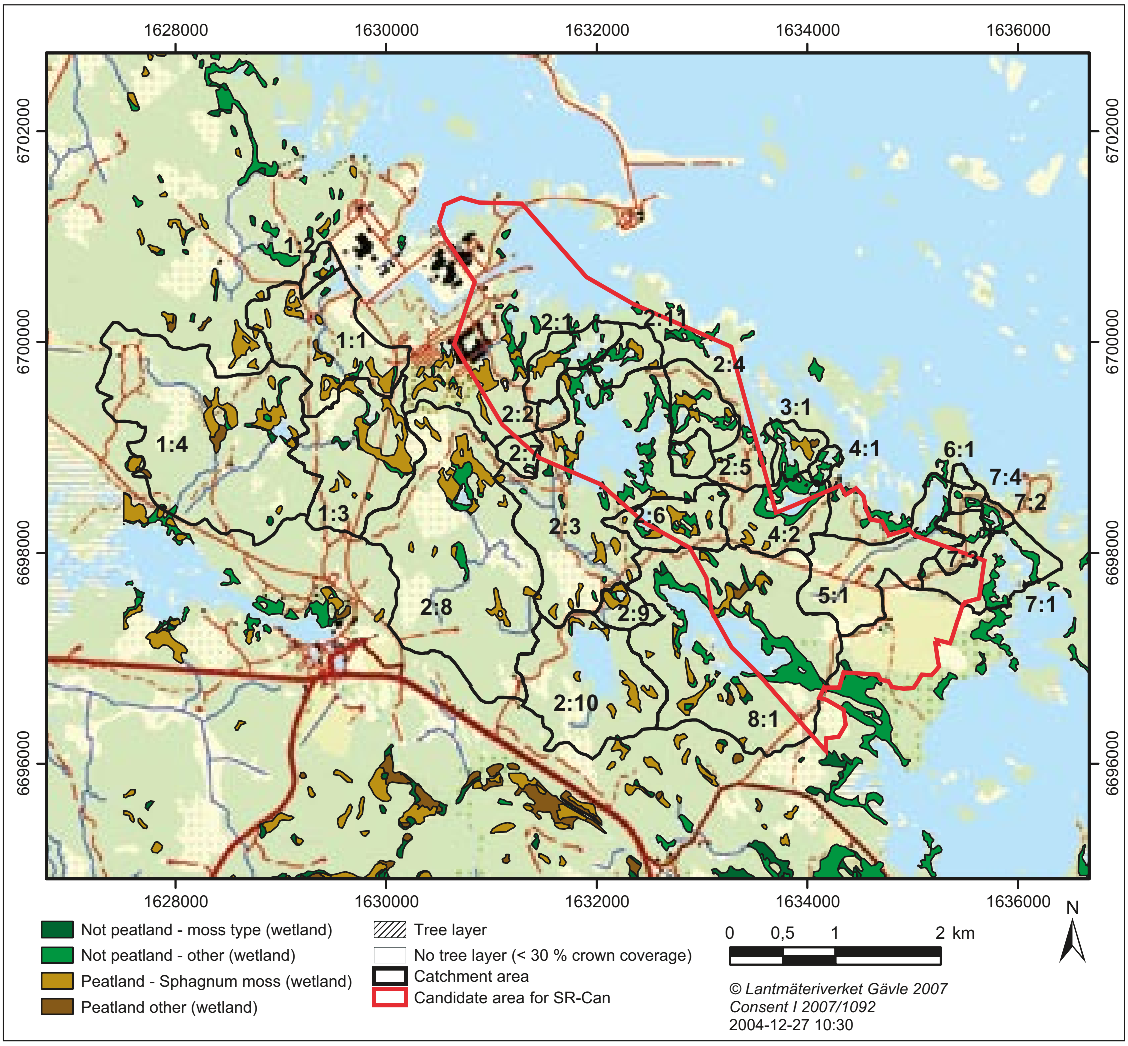


Figure 4-13. *Different types of wetland areas around Forsmark /SKB 2006a/.*

Most lakes in the area are oligotrophic hardwater lakes, in other words nutrient-poor, clear lakes with a high pH and a lot of buffering carbonates. They are often rich in stoneworts, which, together with blue-green algae, form the "algal gyttja" characteristic of these lakes /Brunberg and Blomqvist/, see also /Andersson 2005/. Since the area is flat it is very suitable for studying the process of land uplift and the isolation and silting-up of lakes in the area. An example is Lake Fiskarfjärden just SW of SFR 1, which is of national interest /Brunberg and Blomqvist 1998/.

Most of the wetlands and lakes have been subjected to drainage and water regulation projects aimed at gaining arable land or running water for the iron mills in northern Uppland /Brunberg and Blomqvist 1998/.

Two major rivers, Forsmarksån and Olandsån, drain into Kallrigafjärden Bay south of Forsmark. The annual average discharge from the Forsmarksån River (catchment: 375.5 km²) is 3.0 m³/s and from the Olandsån River (catchment: 880.9 km²) 6.5 m³/s /Larsson-McCann et al. 2002/.

The most commonly occurring large mammal in the area around Forsmark, with the greatest number of individuals, is roe deer /Cederlund et al. 2003/.

Wells

There are both drilled and dug wells in the Forsmark area. Analyses of the well water show that the water quality varies from potable to non-potable. There are wells drilled in rock that exhibit salinities above the taste limit and relatively high calcium and iron contents. Another common problem is infiltration of surface water, which gives a humus taste to the water. Most of the vacation homes in the area have dug wells. The water quality in most of these wells is also poor or non-potable, especially in wells that are not in use. The water quality in a microbiological sense has been judged to be non-potable or of impaired potability due to a very high concentration of coliform bacteria and/or E. coli. Chemically speaking, the water quality in all wells has been deemed to be of impaired potability due to high concentrations of organic substances, iron, manganese, chloride etc /Ludvigsson 2002/.

The groundwater level generally lies very close to the ground surface in the Forsmark area. Measurements in the area have shown that the groundwater level in the soil layers is no deeper than one metre below the ground surface, while it is slightly deeper in the bedrock. The gradient is thus directed downward at many places, except in pronounced discharge areas. However, it is not only the groundwater level that is important for locating wells; geology is also of great importance for well yield. The permeability of the bedrock or the Quaternary deposits must be sufficiently high so that water can run to the well. Well yield can be good in both recharge and discharge areas. The flat topography in the Forsmark area makes it possible to locate wells in both local high-lying areas and low points /SKB 2006a/.

Data on well yield, well depth and the specific capacity for rock wells have been compiled by /Gentzschein et al. 2006/.

Table 4-8 is taken from the report and shows information on the wells, which is also shown in Figure 4-14. Green and black dots in the figure represent data from rock wells stored in the Well Archive /Gentzschein et al. 2006/, for further information see www.sgu.se. Red dots represent data from the site investigation in Forsmark, modelling phase 1.2 /Gentzschein et al. 2006/. What distinguishes the green and black dots is nearness to the candidate area in Forsmark. The location of the green and black dots reflects where people live. The depth to which wells have been drilled in the rock at different places depends on a number of factors, of which the risk of salt water intrusion is significant. This risk increases with depth. Another factor of importance is the water need, a third is the possibility of finding water-conducting fractures.

Interesting parameters are well yield, well depth and specific drawdown. The latter indicates how much water the well yields per metre drawdown of the groundwater level, i.e. Q/s where Q is the well yield in litres per hour and s is the drawdown in metres when Q was measured. Q is usually determined at full drawdown, i.e. when the groundwater level is at the same level as the bottom of the well, i.e. $s \approx D$ where D is well depth.

Table 4-8. Well yield (Q), depth (D) and specific capacity (Q/D) for wells in Östhammar Municipality /Gentzschein et al. 2006/. ÖM (Östhammar municipality) = black dots; GZ (Guard zone) = green dots; FA (Forsmark area) = red dots.

Variable	Category	Number of wells	Median	Average	Min.	Max.
Q (l/h)	ÖM	1,664	500	1,184	1	27,000
	GZ	281	700	1,467	1	10,000
	FA	22	12,300	19,141	216	72,000
D (m)	ÖM	1,664	52	58.6	7	180
	GZ	281	50	52.5	7	131
	FA	22	143	144	26	300.55
Q/D (l/h/m)	ÖM	1,664	9,211	30.78	0	1,687.5
	GZ	281	15	46.04	0	1,142.86
	FA	22	70.95	196.64	2	901.317

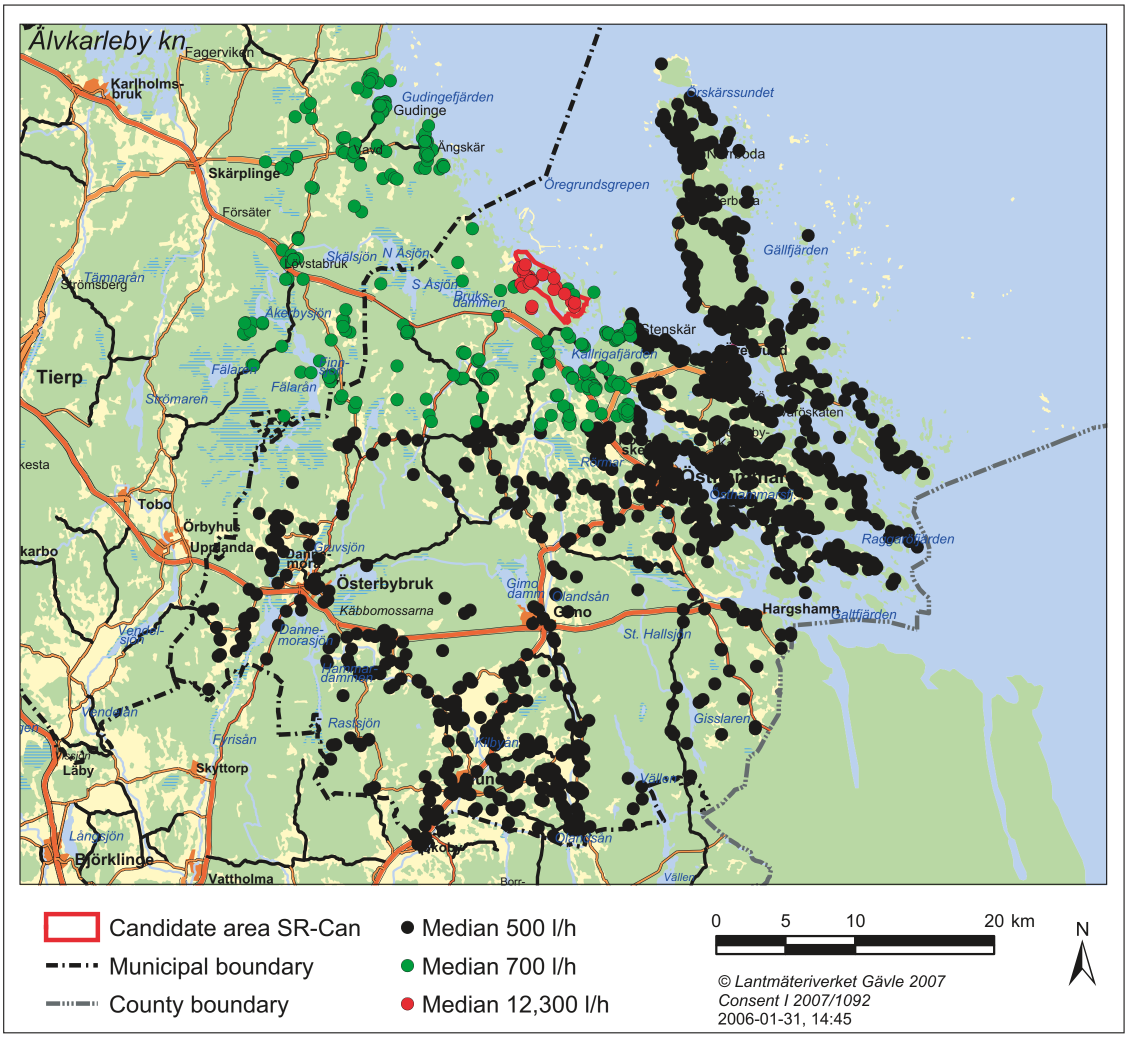


Figure 4-14. *Wells in northern Uppland /Gentzschein et al. 2006/.*

4.7.4 Turnover of organic material

Turnover of organic material can provide a measure of how certain radionuclides, especially C-14, can be spread and cycled in the biosphere, which is why the mass balance and turnover of carbon for the Forsmark area has been studied for both the terrestrial environment and the marine area /Lindborg 2005, Kumblad 2001, Kumblad and Kautsky 2004/.

The studies of carbon turnover in the surface ecosystems show that the residence times for carbon vary widely /Lindborg 2005/. Carbon turnover in the sea was modelled initially for the SAFE study, after which an update has been done /Kumblad and Kautsky 2004/. In the terrestrial ecosystem, the theoretical residence time for carbon is long, up to 10,000 years, while it is much shorter for the aquatic areas, and only a few days for outer near-coastal areas. Mean residence times for fresh water systems can, however, vary widely depending on sediment layers and water residence times /Lindborg 2005/. Accumulation of radionuclides in organic material and water can therefore take place during no more than 10,000 years in the present-day Forsmark area.

4.8 Geology

A large number of geophysical, geological-structural and hydrogeological investigations have been carried out in the Forsmark area (see below) in conjunction with the construction of the nuclear power plant and SFR 1 and during the site investigation for the final repository for spent fuel:

(i) Preliminary investigations and investigations in conjunction with the construction of the power plant (units F1, F2, F3) and cooling water tunnels.

(ii) Preliminary investigations and supplementary preliminary investigations for siting of SFR 1.

(iii) Detailed characterization of encountered fracture zones at SFR 1.

(iv) Geological follow-up of tunnels and rock caverns in SFR 1 and measurement of surrounding groundwater pressures and inflows in the tunnel system in SFR 1.

(v) Site Investigations in Forsmark for the final repository for spent fuel.

The results of these investigations are presented in the following reports:

- With respect to geophysics and geology, the fundamental results are presented in /SKB 1982, Carlsson et al. 1986, Tirén 1989, SKB 2005/.
- With respect to hydrogeology, the fundamental results are presented in reports where groundwater pressures have been recorded in boreholes, see /Arnefors and Carlsson 1985, Carlsson et al. 1986, Andersson et al. 1986, Danielsson 1985, 1986, Danielsson and Larsson 1988, Johansson et al. 2005/.

4.8.1 Quaternary deposits

Investigations of the sea floor at SFR 1 have shown that the rock is for the most part covered by bouldery till with occasional outcrops, see also section 4.7.2.

4.8.2 Existing rock types

The bedrock around SFR 1 is composed of three main rock types /Bodén and Lundin 2007, SKB 2006e/:

(i) Felsic to intermediate metavolcanic rocks formed early during the Svecofennian orogeny. These rock types comprise the area's oldest bedrock and dominate the uppermost 600 metres of the access tunnels.

(ii) Granitoids of Svecofennian age, more or less foliated. The granitoids dominate in the northern half of the repository area and also constitute the dominant rock type in adjacent land areas.

(iii) Pegmatites (coarse-grained rocks) of at least two generations infuse the rock mass. The older pegmatite is partially granitic and constitutes the dominant rock type from about 600 metres into the access tunnels up to the southern part of the repository area.

4.8.3 Fracture zones

The bedrock in the Forsmark area is fractured in a general block-like pattern. The deformation zones (the fracture zones) can be divided into regional (larger than 10 km) and local zones (smaller than 10 km) /Andersson 2003/. The Singö Zone is a steeply dipping regional zone, longer than 10 km. Zones 3, 6, 8 and 9 are steeply dipping local fracture zones. Zone H2 is a local subhorizontal fracture zone, see Figure 4-15. The local zones have been interpreted on the basis of results from investigation boreholes in the near-field and observations in tunnels. Zone 6 intersects four of the disposal tunnels (1BTF, 2BTF, BLA and BMA); zone H2 lies subhorizontally beneath the facility, while the other local zones lie around the facility. The fracture zones around the facility are shown in Figure 4-15.

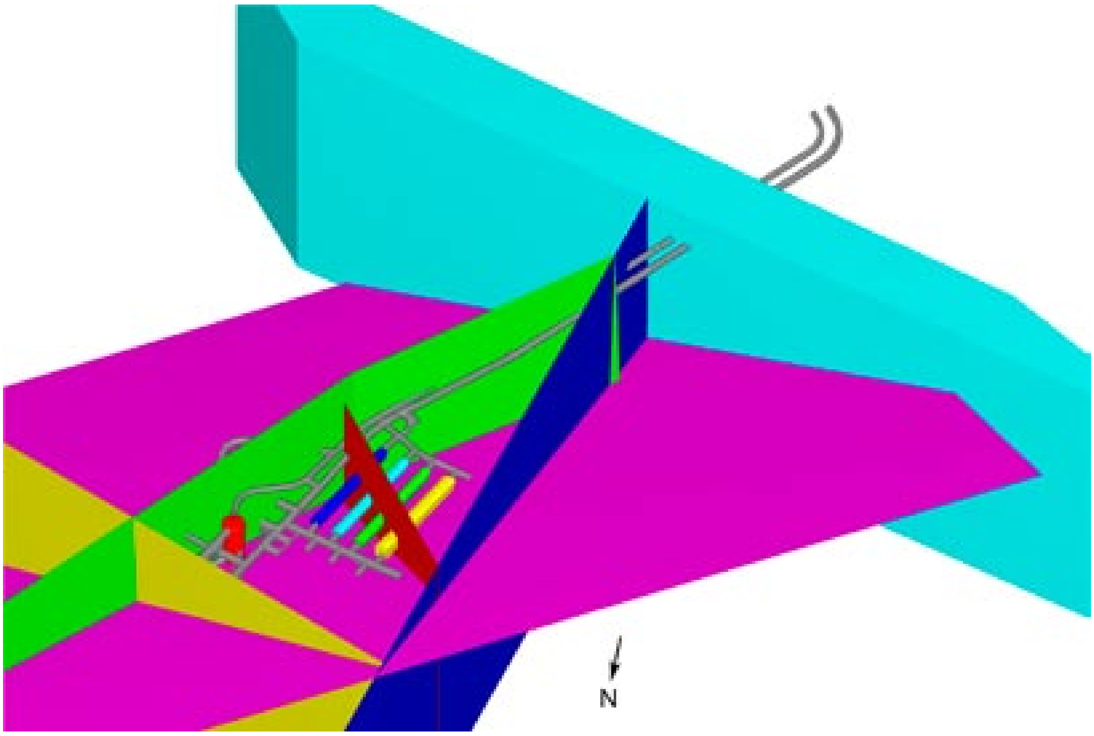


Figure 4-15. Interpreted fracture zones around SFR 1 and the tunnel system at SFR 1 /Holmén and Stigsson 2001a/. FRACTURE ZONES: Purple = H2. Dark blue = 3. Dark red = 6. Yellow = 8. Green = 9. Light blue = Singö Zone. TUNNELS: Grey = Access. Red= Silo. Dark blue = 1BTF. Light blue = 2BTF. Green= BLA. Yellow= BMA.

The fracture zones in the rock around SFR 1 are modelled in the deformation zone model /SKB 2006e/. The fracture zones are also presented in the reports /Holmén and Stigsson 2001a/.

4.8.4 Rock mechanics

The mechanical properties of the rock have been determined on the basis of seismics, mapping and testing of drill cores as well as rock stress measurements. Based on these measurements, a rock mechanical analysis was performed of the rock nearest the silo with connecting tunnels /Stille et al. 1985/.Table 4-9 summarizes some of the values used there for the initial mechanical properties of the rock. The rock mass was judged to be of good quality, which was also confirmed by experience from the rock cavern works when different rock support measures were carried out. Rock vaults and tunnels are reinforced with rock bolts and fibre-reinforced shotcrete. The bolts are made of untreated rebar grouted with cement paste.

A thorough mapping of fractures and fracture zones in the tunnels was done in connection with the geological follow-up after the completed rock construction works /Christiansson and Bolvede 1987/. The mapping showed that most of the fractures contain some type of fracture-filling mineral, usually calcite, chlorite and laumontite.

Table 4-9. Estimated values of the mechanical properties of the rock mass /Stille et al. 1985/.

Parameter	Estimated value MPa
Maximum horizontal stress	10
Minimum horizontal stress	5
Tensile strength of rock mass	10
Deformation module of rock mass	20,000

4.9 Hydrogeology

4.9.1 Near-surface groundwater conditions on land

Till is the dominant type of Quaternary deposit, covering about 75% of the Forsmark area. Boulders occur frequently, but cover only about 5% of the area. Hydraulic conductivity is a measure of the permeability of the rock. Investigations show as expected that hydraulic conductivity is much higher in the upper part of the till than further down. The hydraulic conductivity in the upper part of the till is estimated at 10^{-5}–10^{-4} m/s, while the specific yield is estimated at between 10 and 20%, with the higher values nearer the surface. Based on the measurements of the total porosity of the upper part of the till, the total porosity has been estimated to be between 30 and 40% /Werner et al. 2007/.

Below the uppermost metre in the till, the total porosity and the specific yield are estimated at 20–30% and 2–5%, respectively. Data from the site investigations at Forsmark in conjunction with SR-Can suggest a higher hydraulic conductivity in the contact zone between the Quaternary deposit and the rock than in the till itself. The hydraulic conductivity has a geometric mean value of $1.3 \cdot 10^{-5}$ m/s, while the value for the till is $1.2 \cdot 10^{-6}$ m/s /Werner et al. 2007/.

In Forsmark, precipitation is the main source of water for recharging the groundwater. During the summer, however, the lakes in the area can serve as a source for groundwater recharge in the aquifer in the till in the area immediately surrounding the lakes. Due to low vertical conductivity in the bottom sediments, however, this water exchange is low. The Baltic Sea can also serve as a source of groundwater recharge, especially during periods of high water level /Juston et al. 2007/.

In the Forsmark area, the groundwater levels are near the surface in the soil layers, since there is plenty of water for groundwater recharge during most of the year, small topographical gradients and relatively low hydraulic conductivity. The diurnal variations in groundwater levels clearly show the effect of evapotranspiration on the groundwater during dry periods. An interesting observation is that where it is possible to compare groundwater levels in the soil layers with those in the rock at the same place, the groundwater level in the rock is often considerably lower than in the soil layers. This means that there is a downward groundwater flow /Werner et al. 2007/.

The low regional topographical gradients and the local small-scale topography, in combination with the sharp decline in hydraulic conductivity with depth, both in the Quaternary deposits and in the rock, leads to the formation of local groundwater flow systems. The shallow and highly dynamic groundwater levels in the Quaternary deposits also give rise to variations in time of the size of the recharge and discharge areas in the local shallow groundwater systems /Werner et al. 2007/.

4.9.2 The hydraulic conductivity of the rock

The rock at SFR 1 is a fractured crystalline rock. The groundwater flow in such rock takes place in open fractures in the rock mass, so that the hydraulic conductivity is dependent on the properties of a large number of interconnected open fractures. Thus, the hydraulic conductivity of a given rock volume is dependent on the fracture system inside the studied volume /Gustafson et al. 1989, Wikberg et al. 1991/.

Since the integrated properties of the fracture system vary with the size of the studied rock volume, conductivity is scale-dependent /Holmén and Stigsson 2001a/.

A large number of hydraulic tests have been conducted in the rock mass surrounding the tunnels at SFR 1. The interpreted fracture zones surrounding SFR 1 have been tested hydraulically by straddle-packer tests (3 m between the packers). Twenty such tests have been carried out in zone H2, while fewer tests have been performed in the other zones (two to five tests per zone).

The tests show that zone 3 is the most permeable zone; the three tests performed in this zone give a geometric mean value of the hydraulic conductivity of $2.9 \cdot 10^{-6}$ m/s /Holmén and Stigsson 2001a/. The hydraulic conductivity from previous studies has been summarized in /Holmén and Stigsson 2001a/ for all fracture zones and is presented in Table 4-10.

An analysis of the uncertainty in the calibration of the hydrogeological model constructed in /Holmén and Stigsson 2001a/ is presented in /Holmén 2005/. This study is an inverse modelling of (i) the inflow of groundwater to the tunnel system at SFR 1 and (ii) the estimated hydraulic conductivity for zones and rock mass defined with an uncertainty range. The study shows that the current inflow of groundwater to SFR 1 can be reproduced by hydrogeological models with very different combinations of hydraulic conductivity values for zones and rock mass. Considerable deviations from the estimated hydraulic conductivity values can occur.

A representative mean value of the hydraulic conductivity of the rock mass is dependent on both the studied scale and flow direction of the groundwater. The conductivity of the rock mass between the fracture zones also depends on how fracture zones are defined. One should therefore be careful in giving a general value for the conductivity of the rock mass. However, by studying the inflow of groundwater to the tunnel system for the current situation with drained tunnels, it is possible to estimate an equivalent conductivity (representative mean) for radial flow towards the tunnels. Such a value is applicable on the scale given by the size of the disposal tunnels and the distance to the sea floor. For the rock mass around the tunnels and between the interpreted fracture zones, the hydrogeological model study /Holmén 2005/ gives a hydraulic conductivity value between about $2 \cdot 10^{-9}$ m/s and about $7 \cdot 10^{-9}$ m/s. For the rock mass nearer the sea floor (from the sea floor to a depth of about 25 m beneath the sea floor), the conductivity is estimated to be an order of magnitude greater; these hydraulic conductivity values can be described as equivalent conductivity for the rock mass between fracture zones in the near-field of SFR 1 and for radial flow towards the tunnels /Holmén and Stigsson 2001a, Holmén 2005/.

4.9.3 Groundwater inflow

Measurements of groundwater seepage inflow in SFR 1 are performed according to a monitoring programme. The previously noted declining trend in total pumped-out volumes of water appears to have levelled off. The total flow, which was 44 m^3/h in 1988, has declined to a stable value of about 20 m^3/h in 2006, see Table 4-11, Figure 4-16 and Figure 4-17 /Bodén and Lundin 2007/. The increased inflow in BMA during 2006 (see Table 4-11) can in all probability be explained by the fact that a new water meter was installed in early 2006.

Table 4-10. Hydraulic conductivity and thickness /Holmén and Stigsson 2001a/.

Zone	Hydraulic conductivity [m/s] (geometric mean)	Approximate thickness of the zone (m)]	Number of tests
H2	$3.4 \cdot 10^{-7}$	6	20
3	$2.9 \cdot 10^{-6}$	6	3
6	$2.1 \cdot 10^{-7}$	2	2
8	$5.1 \cdot 10^{-7}$	9	5
9	$9.8 \cdot 10^{-9}$	3	4

Table 4-11. Groundwater seepage 1998–2006 /Bodén and Lundin 2007/.

Values in litres/minute. The abbreviations below refer to various parts of the repository and tunnels.

Measurement point/area	sep-98	sep-99	okt-99	feb-00	sep-00	sep-01	sep-02	sep-03	sep-04	jun-05	jan-06	sep-06	dec-06
BMA (measured)	6.0	6.7			8.0	8.0	6.5	6.5	5.5	5.0		12.0	12.0
BLA (measured 2003–)								0.0	0.0	0.0		0.0	0.0
2BTF (measured 2003–)								9.1	8.6	8.6		8.6	8.6
1BTF (measured 2003–)								3.3	3.2	2.8		2.4	2.4
BLA (–2002) + 1BTF (–2002) + 2BTF (–2002) + BST+CT+DB+UB +3VB+EB+part of ST (calculated)	83.1	79.8			78.7	76.1	72.6	57.9	58.0	56.7		45.3	37.6
UB (measured partial sum)	**89.1**	**86.5**	**87.8**	**87.1**	**86.7**	**84.1**	**79.1**	**76.8**	**75.2**	**71.7**	**76.4**	**68.3**	**60.6**
IB + part of ST and BT (measured)	2.5	3.9			3.4	3.4	2.8	3.6	3.4	3.9		2.2	2.2
BT+DT+STT+TT+2VB (measured)	283.2	276.5			276.5	269.8	244.3	238.1	232.1	203.2		203.2	203.2
Silo walls and bottom (measured in SDT)	1.3	1.1			0.9	1.1	0.9	0.8	0.7	0.8		0.7	0.7
Silo top (measured)	0.1	0.1			0.1	0.1	0.1	0.1	0.1	0.0		0.1	0.1
NBT + SBT (calculated)	90.0	3.8			32.5	25.8	40.9	36.3	24.1	26.1		69.0	79.1
NDB	**377.2**	**285.4**	**314.5**	**316.3**	**313.4**	**300.1**	**289.0**	**278.9**	**260.3**	**244.1**	**285.1**	**275.1**	**285.2**
Total (measured)	**466.3**	**371.9**	**402.3**	**403.4**	**400.1**	**384.2**	**368.1**	**355.7**	**335.6**	**315.8**	**361.5**	**343.4**	**345.8**
– m^3/h	28.0	22.3	24.1	24.2	24.0	23.1	22.1	21.3	20.1	18.4	21.7	20.6	20.7

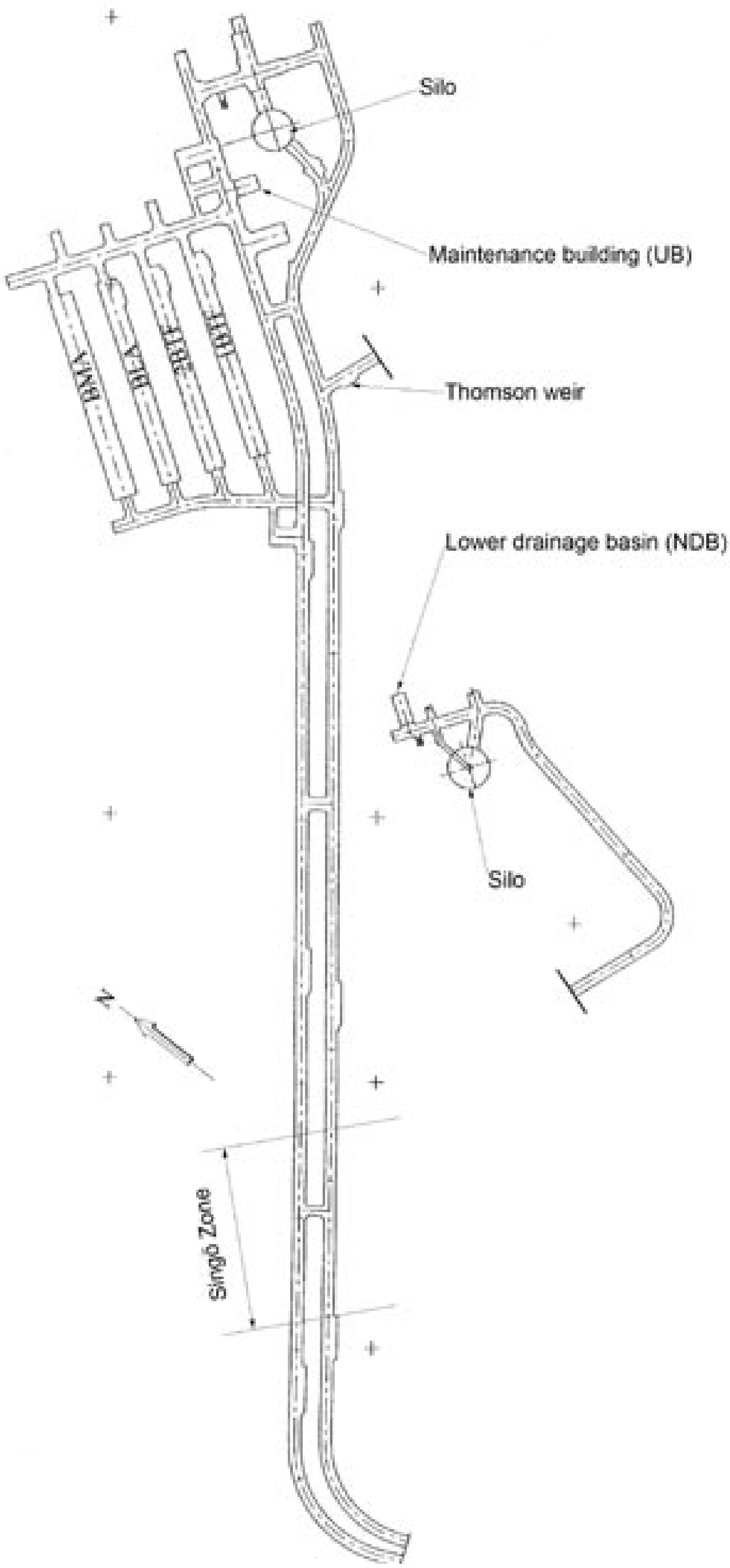


Figure 4-16. Overview of underground part of SFR 1 /Bodén and Lundin 2007/.

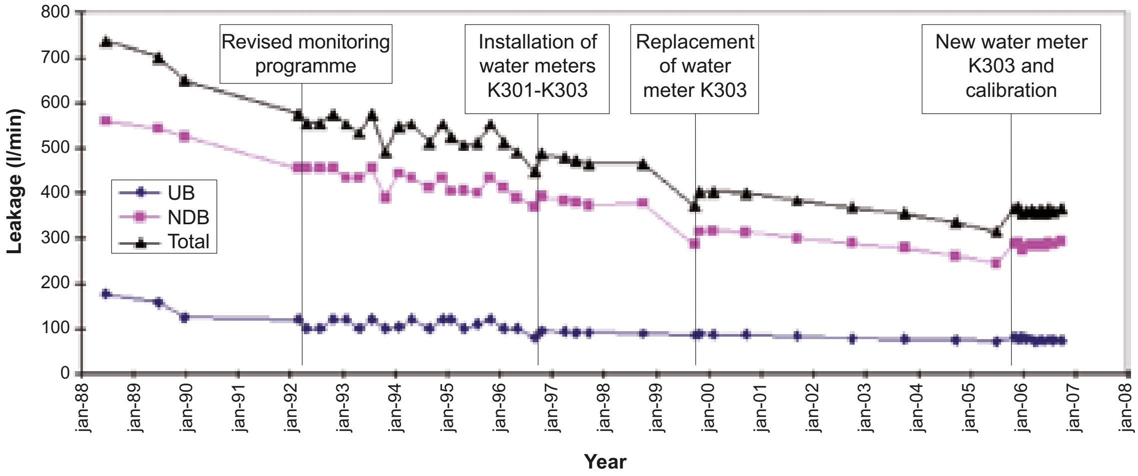


Figure 4-17. *Groundwater inflow to SFR during the period 1988–2006 (UB = maintenance building, NDB = lower drainage basin) /Bodén and Lundin 2007/.*

4.9.4 Groundwater chemistry

Sampling of the groundwater at SFR 1 is done according to a special monitoring programme /SKB 1988/ started in the late 1980s. The samples are taken in boreholes specially intended for analysis of hydrological conditions and chemistry (see Figure 4-18). The holes are fitted with packers that make it possible to study different borehole sections, for example particularly conductive zones. A plastic hose leads from each packered-off section to the mouth of the hole, where the sampling equipment is connected. Annual chemical samplings have been performed since 1996 in four observation points located in four different boreholes. Every fifth year a more extensive sampling is performed that includes all boreholes and borehole sections that yield water. The results are summarized in annual reports for SFR 1, see for example /Nilsson 2005/. The most recent major sampling took place in the autumn of 2006 /Nilsson 2007/. Samplings of the more extensive kind were also performed in 2000 and 1995.

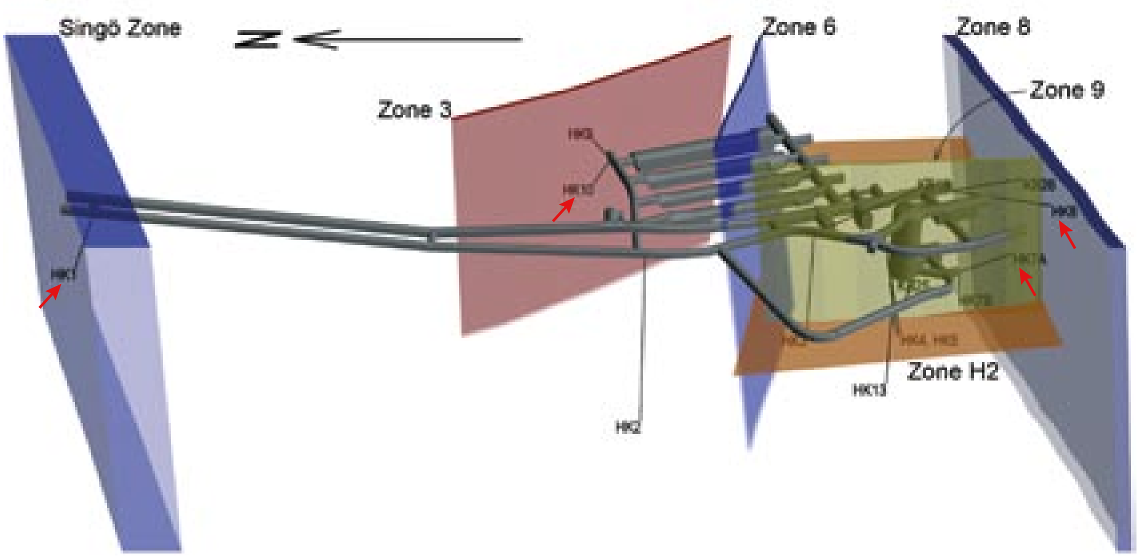


Figure 4-18. *Three-dimensional presentation of the tunnel system in SFR 1 with deformation zones and boreholes. The location of the four boreholes included in the monitoring programme is shown by the red arrows in the figure /Nilsson 2007/. A description of the different zones is provided in /Holmén and Stigsson 2001a/.*

When all values obtained since the start of the monitoring programme in 1989 are compared, only small changes are found in the water composition in the different monitoring points (Table 4-12). The chemical analyses show the changes occurring in the groundwater system around SFR 1. Each of the sampled boreholes represents a special situation. A short description of the different boreholes follows below:

KFR01 (HK 1): The hole enters the conductive Singö Zone, and the water samples show a stable composition with very slightly declining salinity. The change may be due to the fact that the water turnover in the zone is affected by the access tunnels, due to either a very small input of fresh water and/or a slightly larger input of water from Öregrundsgrepen. The very weak transient in the chloride concentration for the Singö Zone shows that its flow regime is only slightly affected by the drawdown in the facility. Since the lowest values of the chloride ion concentration were measured in around 2000/2001, the chloride ion concentration has increased slightly again and now lies around 3.4 g/l /Nilsson 2005/.

KFR7A (HK 7): The borehole represents the conductive zone H2, which is located underneath the facility. Due to the water inflow, deeper and more saline water was initially drawn into the facility. The salinity increased from 5 to 5.5 g/l by 1989. The salinity then declined very slowly until 2000, when it stabilized at a constant level. The slow change is probably due to the fact that a larger fraction of water from Öregrundsgrepen gradually replaces the water that was previously present throughout the rock mass, causing a decline in salinity.

KFR08 (HK 8): The hole enters zone 8, which is in contact with zone H2, and thereby gives a picture of how water from Öregrundsgrepen penetrated into the rock (the zone) long before the water could be detected at greater depths /Wikberg 1999/. Of all the boreholes studied, the groundwater in KFR08 has the salinity and water composition that most resembles the water in Öregrundsgrepen. Furthermore, the salinity has remained more stable than in the other boreholes.

KFR10 (HK 10): The hole represents the situation in the rock (central in facility at mid-height of silo). Up until 1991 the situation in the borehole was more or less steady-state. The change after 1991 has taken place very slowly and resembles the change in KFR01 and KFR7A, i.e. it appears as if a very slow intrusion of water takes place from Öregrundsgrepen, but just as in the case of KFR01 the decrease in chloride ion concentration has levelled off and even started to increase slightly again (cf. Table 4-12).

Groundwater is a blend of waters with different origins when considered over a long enough period of time. Consistently high magnesium concentrations indicate that the groundwater in SFR 1 is mainly of marine origin. In the cases when the chloride concentrations are moreover higher than in Öregrundsgrepen, this indicates that the groundwater contains a considerable fraction of connate marine water from the Littorina Sea (about 7,000 years ago). Relatively high concentrations of O-18 also suggest a marine origin. The boreholes that exhibit the lowest concentrations of O-18 and tritium are all located in rock between zones and often relatively deep down. Here there is probably a larger fraction of glacial meltwater and possibly also more deep salt water not of marine origin. Moreover, low tritium concentrations indicate that the fraction of modern surface water is very low.

The results of the most recent water analyses in 2006 for the most important components from all boreholes are given in Table 4-13 /Nilsson 2007/. Drainage of the facility is expected to lead to a gradual change towards the composition in the sea above the repository.

Table 4-12. Measured chloride ion concentration (mg/l) /Nilsson 2007/.

Year	KFR01 (HK1)	KFR7A (HK7)	KFR08 (HK8)	KFR10 (HK10)
1989	4,090	5,380	3,170	4,430
1990	3,950	5,300	3,100	4,210
1991	3,870			
1992	3,840	5,240	3,150	4,030
1994	3,840	5,190	3,120	
1995	3,767	5,045	3,106	4,180
1996	3,660	4,850	2,950	
1997	3,630	4,670	2,920	
1998	3,590	4,590	2,840	
1999	3,550	4,700	3,230	3,860
2000	3,530	4,460	3,160	3,905
2001	3,300	3,900	2,800	3,400
2002	3,400	4,000	2,800	3,700
2003	3,430	3,960	2,920	3,870
2004	3,442	3,950	2,823	4,017
2005	3,359	3,940	2,821	4,010
2006	3,421	4,030	3,033	4,138

Table 4-13. Chemical composition of the groundwater in all investigated boreholes in SFR 1 and in Öregrundsgrepen in 2006 (ion concentrations in [mg/l] unless otherwise stated) /Nilsson 2007/.

Parameter	Measured values 2006	
	SFR 1	Öregrundsgrepen
pH	7.4–7.6	7.8
HCO_3	69–133	80
SO_4	170–480	430
Cl	2,790–4,200	2,900
F	1.01–1.50	–
Na	1,320–1,610	1,600
K	6–33	63
Ca	320–1,050	90
Mg	106–190	200
Mn_{tot}	0.7–2.9	–
Fe	0.43–3.5	–
Tritium (^3H)	1.7–10	13
δO-18 (‰ SMOW)*	–8.0 – –13.9	–8

* SMOW = Standard Mean Ocean Water.

5 Safety functions and safety performance indicators

5.1 Introduction

The terms “safety functions” and “safety performance indicators” (called safety function indicators in SR-Can) were introduced in the safety assessment of the KBS-3 repository for spent nuclear fuel, SR-Can /SKB 2006a/, where a more detailed description than the following one is provided. Safety functions and safety performance indicators pertain to the period after the repository has been closed (the post-closure period).

In this chapter, similar terms and methods are applied to the final repository for radioactive operational waste, SFR 1. In contrast to a KBS-3 repository, where safety is largely based on total isolation of the radionuclides, safety in SFR 1 is based on a limited quantity of activity and retardation of the radionuclides by the engineered barriers and the surrounding rock. This retardation is achieved by means of limited water flows and sorption on different materials.

A general description of the use of safety performance indicators is provided in section 5.2. The safety functions of SFR 1, along with the safety performance indicators, are presented in section 5.3. Section 5.4 discusses which processes in the evolution of the repository are important to analyze based on the safety performance indicators.

5.2 Safety functions, safety performance indicators and criteria for safety performance indicators – general

The overall criterion for evaluating repository safety is SSI’s risk criterion, which requires that: “*the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk*”. An evaluation of this overall criterion is based on lots of detailed analyses where the final risk is an integrated result of a number of different evaluations which in turn use a large set of input data.

5.2.1 Safety functions

A complete description of how the principal safety functions of limitation and retardation are achieved by various components in the repository system is required for a detailed and quantitative understanding and evaluation of repository safety. Based on an understanding of the properties of the components and the long-term evolution of the system, a number of safety functions that are subordinate to limitation and retardation can be identified in SR-Can.

In this respect, a *safety function* is defined as the qualitative role whereby a repository component contributes to safety. An example is the bentonite in the silo walls, which contributes to reducing advective transport of solutes out of the repository. The safety function is then the ability to *restrict advective transport*.

5.2.2 Safety performance indicators

In order to be able to evaluate safety, it is desirable to be able to express or relate the safety functions to measurable or calculable quantities. In the case of the ability of the bentonite wall to restrict advective transport, hydraulic conductivity is a suitable quantity to use to judge whether this safety function is upheld. The hydraulic conductivity of the bentonite is therefore defined as a *safety performance indicator* for this safety function. A safety performance indicator is thus a measurable or calculable quantity by means of which a safety function can be evaluated.

5.2.3 Criteria for safety performance indicators

In order to determine whether a safety function is upheld or not, it is desirable to have a quantitative criterion against which the safety performance indicator can be evaluated over the period of time covered by the safety assessment.

However, the situation is different from other kinds of technical safety evaluations in one important respect: the performance of the repository components does not generally change in discrete increments. The repository will change continuously and there is no clear distinction between an acceptable and a deficient performance for the individual barriers. It may therefore be difficult or impossible to define relevant criteria for several safety performance indicators.

Therefore, no criteria for safety performance indicators have been defined for SFR 1 in this assessment. The main purpose of the safety performance indicators is to guide the definition of scenarios. This has been done by comparing the state of the performance indicator with what has been assumed in the reference evolution. In principle, this means that alternative scenarios are generated by the fact that the safety performance indicators deviate from the state in the reference evolution.

5.2.4 Derivation of safety functions and safety performance indicators

In order for the safety functions and the safety performance indicators to be useful in the evaluation of long-term safety, they should include as many aspects of long-term safety as possible. It is therefore important to have a systematic approach to arriving at the safety functions.

The cornerstones in the derivation of the safety functions are:

1. The two main safety functions of limitation and retardation on which the design of SFR 1 is based.
2. The knowledge base that exists on the long-term evolution of SFR 1.

5.2.5 Summary

The following definitions have been introduced:

- A safety function is a role by means of which a repository component contributes to safety.
- A safety performance indicator is a measurable or calculable property of a repository component that is used to indicate the extent to which a safety function is fulfilled.

Safety functions contribute to the safety evaluation, but they are neither necessary nor sufficient to establish that the repository is safe.

5.3 Safety functions for SFR 1

In contrast to a KBS-3 repository for spent nuclear fuel, where total isolation of the waste is the most important overall safety principle, safety in SFR 1 is based on the limited quantity of activity in the waste and retardation of releases of radionuclides by the engineered barriers and the geosphere. The conclusions from the use of safety performance indicators in SR-Can /SKB 2006a/ were that it is simpler and more straightforward to define criteria for safety functions that pertain to isolation than those that pertain to retardation. This is due to the fact that isolation is either intact or breached, while retardation changes gradually so that it is difficult or impossible to define what acceptable performance is.

However, the method employing safety functions and safety performance indicators has proved to be a good tool for analyzing the future function of a repository and for arriving at a comprehensive set of scenarios. This section presents a set of safety functions and safety performance indicators for SFR 1. The main idea here is to express the original safety philosophy for SFR 1, supplemented with newfound knowledge of the long-term evolution of the repository, as a set of safety functions.

The safety functions of SFR 1, in contrast to those of KBS-3, are not general for the entire repository. The different repository parts have different safety functions. The low flow in the geosphere and the repository's location relative to the shoreline are the same for all parts. The different safety functions in the different repository parts are:

1. BLA: Limited waste quantity.
2. BTF repositories: Limited waste quantity and hydraulic and chemical function of concrete tanks.
3. BMA: Limited waste quantity and hydraulic and chemical function of concrete structures.
4. Silo: Limited waste quantity, hydraulic function of silo wall of bentonite and chemical function of concrete structures.

The engineered barriers or other components that have a safety function are illustrated in Figure 5-1.

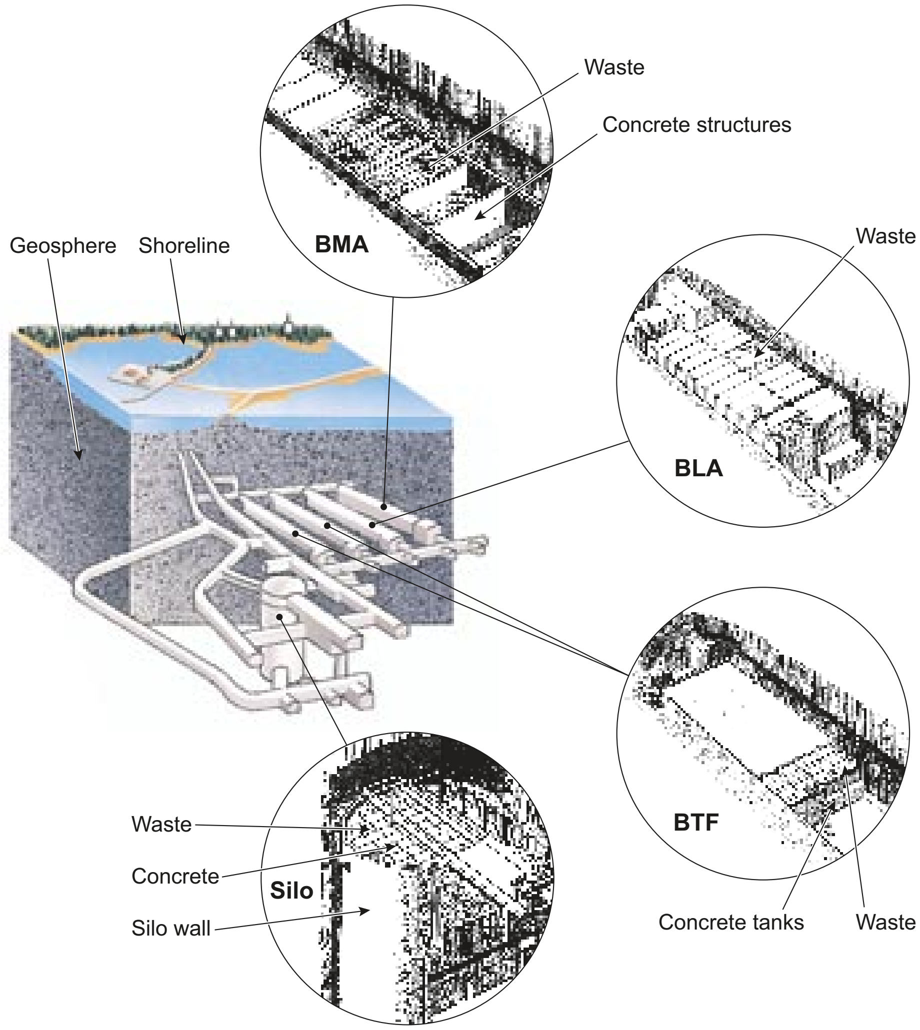


Figure 5-1. *Illustration of the engineered barriers or other components that have a safety function in SFR 1. The waste in BLA has the safety function "limited waste quantity"; in the BTF repositories, there is a limited waste quantity and hydraulic and chemical function of concrete tanks. In BMA, there is a limited waste quantity and hydraulic and chemical function of concrete structures. In the silo there is a limited waste quantity, hydraulic function of the silo wall of bentonite and chemical function of concrete structures. The geosphere and the position of the shoreline are also associated with safety functions.*

5.3.1 The waste

The limited quantity of activity that may be deposited in SFR 1 is a prerequisite for the safety of the repository, and the quantity of activity in the different waste parts has therefore been selected as a performance indicator. Table 5-1 shows the activity quantity stipulated in the radiation protection requirements /SSI 2003b/. Exceeding this quantity could be classified as an unfulfilled safety function. The reason for the choice is that this activity has resulted in a "safe repository" according to previous analyses.

5.3.2 Geosphere

A low groundwater flow through the repository is a prerequisite for its safe function. This is particularly true of BLA, which lacks other retardation functions. Two safety performance indicators that control the groundwater flow in the geosphere have been considered:

Hydraulic gradient

The site of SFR 1 was selected partly because of the low hydraulic gradient. The direction and magnitude of the gradient change due to shoreline displacement, however. Today, when SFR 1 is below the sea floor, the gradient is slightly upward-directed. After about 1,000–2,000 years the gradient is expected to increase and be more horizontal. In this later phase the gradient is also expected to be controlled more by the local, rather than the regional, topography.

Table 5-1. The limitations that apply to SFR 1 /SSI 2003b/.

Nuclide	Total [Bq]	Silo [Bq]	BMA [Bq]	BTF (1BTF+2BTF)	BLA [Bq]
H-3	$1.3\cdot10^{14}$	$1.3\cdot10^{14}$			
C-14	$7.2\cdot10^{12}$	$6.8\cdot10^{12}$	$2.9\cdot10^{11}$	$1.3\cdot10^{11}$	$2.6\cdot10^{9}$
Fe-55	$8.3\cdot10^{14}$	$7.1\cdot10^{14}$	$1.0\cdot10^{14}$	$1.7\cdot10^{13}$	$2.3\cdot10^{12}$
Ni-59	$8.0\cdot10^{12}$	$6.8\cdot10^{12}$	$1.0\cdot10^{12}$	$1.5\cdot10^{11}$	$2.3\cdot10^{10}$
Co-60	$2.1\cdot10^{15}$	$1.8\cdot10^{15}$	$2.6\cdot10^{14}$	$4.0\cdot10^{13}$	$5.8\cdot10^{12}$
Ni-63	$7.3\cdot10^{14}$	$6.3\cdot10^{14}$	$8.8\cdot10^{13}$	$1.5\cdot10^{13}$	$1.9\cdot10^{12}$
Sr-90	$2.6\cdot10^{14}$	$2.5\cdot10^{14}$	$6.5\cdot10^{12}$	$2.7\cdot10^{12}$	$7.1\cdot10^{10}$
Nb-94	$8.0\cdot10^{9}$	$6.8\cdot10^{9}$	$1.0\cdot10^{9}$	$1.5\cdot10^{8}$	$2.3\cdot10^{7}$
Tc-99	$3.4\cdot10^{11}$	$3.3\cdot10^{11}$	$8.8\cdot10^{9}$	$3.6\cdot10^{9}$	$1.1\cdot10^{8}$
Ru-106	$6.3\cdot10^{12}$	$6.1\cdot10^{12}$	$1.7\cdot10^{11}$	$6.2\cdot10^{10}$	$2.1\cdot10^{9}$
I-129	$2.0\cdot10^{9}$	$1.9\cdot10^{9}$	$4.7\cdot10^{7}$	$2.2\cdot10^{7}$	$6.4\cdot10^{5}$
Cs-134	$8.2\cdot10^{14}$	$8.1\cdot10^{14}$	$2.2\cdot10^{12}$	$1.1\cdot10^{13}$	$2.6\cdot10^{11}$
Cs-135	$2.0\cdot10^{10}$	$1.9\cdot10^{10}$	$5.3\cdot10^{8}$	$2.2\cdot10^{8}$	$6.4\cdot10^{6}$
Cs-137	$5.1\cdot10^{15}$	$4.9\cdot10^{15}$	$1.3\cdot10^{14}$	$5.3\cdot10^{13}$	$1.7\cdot10^{12}$
Pu-238	$1.2\cdot10^{12}$	$1.2\cdot10^{12}$	$3.1\cdot10^{10}$	$1.7\cdot10^{10}$	$4.7\cdot10^{8}$
Pu-239	$4.0\cdot10^{11}$	$3.8\cdot10^{11}$	$1.2\cdot10^{10}$	$6.9\cdot10^{9}$	$1.9\cdot10^{8}$
Pu-240	$8.1\cdot10^{11}$	$7.8\cdot10^{11}$	$1.9\cdot10^{10}$	$1.1\cdot10^{10}$	$2.9\cdot10^{8}$
Pu-241	$4.3\cdot10^{13}$	$4.2\cdot10^{13}$	$9.4\cdot10^{11}$	$5.4\cdot10^{11}$	$1.5\cdot10^{10}$
Am-241	$1.0\cdot10^{12}$	$1.0\cdot10^{12}$	$2.4\cdot10^{10}$	$1.3\cdot10^{10}$	$3.8\cdot10^{8}$
Cm-244	$1.2\cdot10^{11}$	$1.2\cdot10^{11}$	$2.8\cdot10^{9}$	$1.5\cdot10^{9}$	$4.4\cdot10^{8}$
Total	$1.0\cdot10^{16}$	$9.2\cdot10^{15}$	$6.0\cdot10^{14}$	$1.4\cdot10^{14}$	$1.2\cdot10^{13}$

Large local gradient variations can be expected within the repository. The gradient inside a permeable tunnel is very small, while the gradient in the rock outside the tunnel is large. Furthermore, water flows in and out through the tunnels in different sections, which naturally means that the gradient varies inside the tunnel system as well. Given these facts, it is not judged meaningful to define any criterion for the gradient, nor is this required according to the introduction to section 5.3. The performance indicator "limited gradient" marks that this is an important factor that affects the flow and thereby, by extension, the function of the repository.

Fracture transmissivity

The flow through the different parts of the repository is dependent on, among other things, the transmissivity of the fractures in the rock, the connectivity of the fracture network, and how this network is interconnected with the repository area. However, fracture transmissivity and connectivity vary in the rock, which means that it is practically impossible to define any meaningful criterion. The performance indicator "limited fracture transmissivity" marks that this is an important factor that affects the flow and thereby, by extension, the function of the repository.

5.3.3 Engineered barriers – hydraulic function

The different engineered barriers in the repository constitute obstacles to the release of radionuclides. Nuclides that are enclosed in moulds and other closed packages must first diffuse out of the packages. In the repository parts that are designed as closed volumes, such as the silo, transport is further hindered by the low hydraulic conductivity of the outer walls. A property that all engineered barriers have in common is that they contribute to safety by means of the safety function "limited advective transport", and they have a common safety performance indicator, hydraulic conductivity.

The low flow through BTF and BMA is partially controlled by the hydraulic conductivity of concrete tanks and compartments. Increased conductivity results in increased flow, but there is no exact value where the function can be regarded as lost.

BLA

In BLA the engineered barriers do not have any safety function.

BTF

Concrete tanks with dewatered ion exchange resins and steel drums with ashes are placed in BTF. Concrete tanks are set up so that they form rooms with ash drums. The containers are grouted with permeable concrete. The concrete walls in the tanks, together with the grout, constitute the engineered barrier here and the low hydraulic conductivity in the walls of the concrete tanks constitutes the safety performance indicator.

BMA

In BMA the radioactive waste is stored in concrete compartments that are covered with prefabricated concrete blocks and overcast with concrete. The engineered barriers are the waste package – consisting of waste, drums and moulds – and concrete walls. All these parts restrict the transport of water through the waste. In this analysis, however, only one safety function is defined for the concrete walls. The low hydraulic conductivity in the concrete is the safety performance indicator.

In intact concrete, the conductivity is so low that diffusion is the dominant transport mechanism. But concrete is not a self-healing material in the same way as bentonite, and the possibility cannot be excluded that there are cracks in the concrete walls, which could dominate the mass transport.

Silo

Most of the waste in the silo is solidified in concrete or bitumen. The waste is surrounded by the following engineered barriers:

- Waste package
- Grouting concrete and compartment walls
- Concrete silo walls
- Bentonite or sand/bentonite buffer

In the silo, a safety function can be attributed to the concrete walls and the bentonite buffer. But the main limitation comes from the bentonite, so no safety function is used from the concrete (although the concrete walls could be handled in the same way as the walls in BMA, see above). The hydraulic conductivity of the bentonite comprises a safety performance indicator. The buffer in the walls can in principle be taken into account in the same way as the bentonite buffer in a KBS-3 repository, which is described in /SKB 2006f, section 2.3.2/.

In order that the silo will retain its physical integrity and the water will not be pressed out due to gas pressure, gas generated by corrosion and degradation of the waste must be able to escape without causing any appreciable pressure build-up. If the gas pressure exceeds 50 kPa, there is a risk that the silo will not perform as intended /Pusch 1985/. Gas pressure is a safety performance indicator for limited advective transport in the silo.

Temperature

A prerequisite for the engineered barriers to retain their hydraulic function is that they do not freeze. Frost damage can occur in concrete if the freezable water quantity is greater than 5 l/m^3 /Emborg et al. 2007/. Already at temperatures below –5°C, the freezable water quantity in the concrete is 17 l/m^3 in SFR 1, which means that it will suffer permanent damage. Temperature is a safety performance indicator for limited advective transport in the silo.

All water in the bentonite in the silo does not freeze at 0°C; the fraction of water that freezes increases with decreasing temperature. In clays, this is mainly due to the surface effects of the clay particles /Emborg et al. 2007/. In the case of temperatures in the range –5 to –10°C, the expansion caused by gradual freezing of a fraction of the water in the bentonite will not cause any appreciable volume increase in the bentonite. The volume increase causes water to be forced out of the bentonite as the frost front passes the repository and ice is formed. As far as the bentonite itself is concerned, its function will probably not be appreciably altered by its having frozen and subsequently thawed.

In addition to the fact that some of the water in the bentonite freezes when the temperature falls below 0°C and thereby expands, and in this case is gradually forced out of the bentonite, the reverse process also takes place. This entails that water is sucked into the freezing bentonite, where it accumulates in ice layers that gradually grow in thickness. The ice layers normally grow in a direction parallel to the heat flow. In this case, where we can expect a largely horizontal frost front, the ice layers will therefore grow in thickness vertically. The driving force for this process comes from the unfrozen water, which has a potential that is lower than that in the surrounding free water. This lower potential is a consequence of the fact that the water does not freeze at 0°C but at a lower temperature. The phenomenon is common in natural soil layers and is then termed frost heave. The magnitude of frost heave is dependent on several factors.

The most important ones are:

- the temperature gradient and thereby the speed of the frost front,
- the supply of water,
- the composition of the soil material that freezes,
- overburden pressure,
- time available for freezing.

The frost heave in the silo can therefore not be linked directly to a certain temperature. In order for it to have any appreciable effect in SFR 1, a long time is required for freezing. The important thing here is not the absolute value of the frost heave, but the realization that it is necessary to take into consideration the possibility that frost heave will occur in the repository and that the rock mass above the repository may be lifted. This can open up both new and old fractures in the rock mass. During a glaciation, these fractures are filled with ice and are not likely to increase radionuclide transport around the silo. When the permafrost thaws, the ice melts. During this process it is not likely that all fractures will close completely. This means that they will not have the same appearance, thickness and conductivity as before freezing. Frost heave can be of great importance for the performance of the silo, but the process cannot be expressed with a specific performance indicator.

Waste packages

The waste packages in SFR 1 belong to the engineered barriers. They contribute to safety by retarding the outward transport of radionuclides. Concrete moulds can contribute with considerable retardation, while the effect of steel drums is more limited. However, the most important engineered barriers are the tanks, the compartments and the silo walls, as mentioned above. The properties of the waste packages are therefore not counted as a safety function in this assessment.

5.3.4 Engineered barriers – chemical function

Sorption of radionuclides is one of the most important retarding safety functions in SFR 1. Sorption takes place primarily inside the different repository parts, and is not due solely to the design of the repository but also to the properties of the waste and the chemical composition of the groundwater. A prerequisite for good sorption is a favourable chemical environment.

Sorption of radionuclides will occur in all repository parts and in the surrounding rock. But the greatest potential for sorption exists in the repository parts that contain cement. The safety function "good sorption" is therefore defined as sorption on cementitious material, which includes concrete walls, grout and waste packages. Many radionuclides sorb very strongly in bentonite, rock and aggregate. Credit is taken for this in the nuclide transport calculations, but it has not been defined as a safety function in this assessment because sorption on cement is assumed to dominate compared with sorption on other materials.

The importance of the safety function "good sorption" in concrete barriers is strongly linked to the chemical properties of the individual radionuclides. Some nuclides will not sorb under any conditions, in which case the safety function does not exist at all. But most radionuclides can be assumed to sorb very strongly under the conditions that exist in SFR 1. For many radionuclides, sorption is linked to the chemical environment in the repository, and several safety performance indicators are therefore based on the properties of the chemical environment. The different nuclides will, however, be affected in different ways by the chemical environment. The nuclide-specific values of the sorption coefficients are linked to a number of chemical safety performance indicators, see Table 5-2.

Table 5-2. Sorption coefficients for cement and concrete (kg/m³) /Cronstrand 2005/.

	Great influence of pH	Great influence of redox potential	Great influence of complexing agents
H			
C org			
C inorg			
Cl			
Co			
Ni	x		
Se			
Sr			
Mo			
Nb	x		
Tc(IV)		x	x
Ag			
Sn	x		
I			
Cs			
Ho	x		x
Np(IV)	x	x	x
Pu(IV)	x	x	x
Am			x

High pH

In general, cations sorb best at higher pHs, while the opposite applies to anions. In natural waters, however, where organic ligands and carbonates occur, it is not certain that sorption increases with pH, since these ligands bind cations and thereby reduce their sorption, and complexation also increases with pH. The chemical environment in the cement pores, high pH and high calcium concentrations, necessarily means that the carbonate concentration is low, since it is regulated by the calcite equilibrium. Carbonate is otherwise a strong complexing agent and could prevent the sorption of numerous radionuclides. In the same way, high pH values and high calcium concentrations keep the concentration of numerous other ligands low, such as oxalate. Other ligands, such as α-isosaccharinic acid, sorb to cement, possibly by complexation with calcium-rich solid phases. In summary, due to its unique chemical properties, cement has proved to be excellent for keeping down the concentration of ligands that can prevent the sorption of numerous radionuclides. As long as the cement matrix is not degraded, the pH in the pores will be higher than about 10.5, and high pH is therefore an indication that the sorption properties in SFR are favourable.

Reducing conditions

Some of the radionuclides are redox-sensitive, and for some sorption is much weaker under oxidizing conditions. A low redox potential in the engineered barriers is expected to be maintained by the presence of metallic iron and organic material. Sorption of uranium, plutonium, neptunium and technetium would decrease considerably under oxidizing conditions.

Low concentrations of complexing agents

Organic compounds from degradation of the waste form (particularly cellulose) could form complexes with the radionuclides and in this way compete with sorption on solid surfaces. It is important to keep the quantity of complexing agents at low levels. The most important organic complexing agent is isosaccharinic acid /Cronstrand 2005/.

Available sorption surface

Sorption always takes place on the surfaces of solid phases. Cement has a relatively large porosity, and several of the solid phases of which cement consists are amorphous and have a large specific surface area, which favours sorption. With time, most of the solid phases in cement are slowly transformed into more crystalline substances, and a decrease in sorption capacity can be expected. Degradation of cement that results in precipitations that reduce porosity can also contribute to a reduction in sorption capacity.

5.3.5 Wells

In a relatively long time perspective, all outward transport of radionuclides is expected to end up in the Baltic Sea. This is generally positive for the risk from the repository, but is not regarded as a safety function. In the planning of SFR 1, however, a location beneath the Baltic Sea was considered to be favourable in the sense that no wells could be drilled down to the repository before the process of land uplift had reached the point where the repository is beneath land.

The absence of wells in the actual repository is therefore considered to be a safety function. The performance indicator is the location of the repository in relation to the shoreline.

5.4 Summary, important process to evaluate over time

The methodology of safety functions and performance indicators from SR-Can /SKB 2006a/ has been applied in somewhat modified form to SFR 1. SFR 1 has been divided into a number of components (barriers), each of which has been ascribed one or more safety functions. One or more safety performance indicators have been defined for the safety functions. They are summarized in Table 5-3.

Table 5-3. Components, safety functions and safety performance indicators.

Component	Safety function	Performance indicator
Waste	Limited quantity of activity	Activity in repository part
Geosphere	Low flow in repository parts	Hydraulic gradient
		Fracture transmissivity
Engineered barriers – hydraulic function	Limited advective transport	Hydraulic conductivity of concrete tanks in BTF
		Hydraulic conductivity of concrete walls in BMA
		Hydraulic conductivity of bentonite
		Temperature (bentonite)
		Temperature (concrete)
		Gas pressure in silo
Engineered barriers – chemical function	Good sorption in concrete barriers	High pH
		Reducing conditions
		Low concentrations of complexing agents
		Available sorption surface area
Biosphere	No wells	Location in relation to shoreline

The safety functions and the safety performance indicators provide guidance on what processes to study in the assessment. The quantity of activity in the waste will decrease with time. But it is important to take into account the uncertainties in inventories and their distribution between repository parts. In the geosphere it is important to study the heterogeneity of the flow in the repository and the change in the hydrological conditions with time. For the engineered barriers, degradation with time is one of the most important processes. Sorption is strongly linked to changes in the chemical conditions in the repository.

In a very long time perspective, it is obvious that a number of the safety functions in SFR 1 will be lost. It is therefore necessary to carry out the assessment of repository performance on different time scales. This is described in Chapter 6, section 6.1.

6 Reference evolution for the repository and its environs

6.1 Introduction

The reference evolution is a reasonable example of how the repository may evolve in the future and what consequences this evolution will have for repository safety. In order to keep this chapter from being too large, radionuclide transport and dose calculations are left until Chapter 8. The chapter instead begins with a presentation of the external conditions that constitute the basis for the description of the repository's evolution. The description of the external conditions or the evolution of the environs concerns shoreline displacement and the evolution of the climate. This is followed by a description of how the surface ecosystem is expected to evolve. An important time scale for climate evolution is the time for a complete glacial cycle, which is around 100,000 years. The reference evolution described here offers two alternatives: one where the latest glacial cycle, including the Weichselian glaciation, is repeated and one where the anthropogenically increased greenhouse effect is taken into consideration /SKB 2006a/.

In the opinion of both SKB and the regulatory authorities, the first thousand years are the most important period and require the most detailed analysis, see section 2.3.1. We have chosen to divide the subsequent time into two periods in order to shed light on the changes in climate an ice age would entail. The presentation of the evolution of the repository has thus been divided into a total of three periods:

- The first 1,000 years after closure. During the first thousand years after closure the climate is expected to remain temperate. Most of the activity will decay and the engineered barriers are expected to retain their properties.
- The period from 3,000 AD to 20,000 AD. According to both of the alternative reference evolutions for the climate, the climate continues to be temperate, possibly with some sporadic shallow permafrost. During this period the engineered barriers may degrade and the shoreline may be considerably displaced.
- The period from 20,000 AD until around 100,000 AD. During this period the repository is expected to be frozen during long periods and the degradation of the engineered barriers to be extensive.

For each period, a description is given of the evolution of the repository and its environs and an evaluation is made of the status of the safety functions defined in Chapter 5. The descriptions of the evolution of the repository have been divided into thermal, hydrogeological, mechanical and chemical (THMC) evolution. The descriptions are comprehensive, but important information for the continued assessment is summarized at the end of the account for each period together with the status of the safety functions.

6.2 External conditions

The external conditions on the site affect the evolution of the repository. Shoreline displacement and the climate are particularly important conditions for SFR 1, and they are therefore described here. Important external conditions were identified by an examination of FEPs, see Chapter 3.

The external conditions at SFR 1 will change significantly during the period being analyzed in the safety assessment. At the beginning of the assessment, shoreline displacement is the most important external condition, while climate evolution is the most important in the longer term.

Today it is not possible to forecast the evolution of the climate over the long time spans the safety assessment needs to cover. It is, however, highly likely that the evolution of the climate over the next 100,000 years will include periods of temperate conditions, periglacial conditions with permafrost, glaciation and transitions between these climate domains. The reference evolution therefore includes these periods and transitions. As in SR-Can /SKB 2006a/, reconstructed conditions for the past 120,000 years, including the Weichselian glaciation and the Holocene interglacial, have been used as a reference evolution for the climate. The reference evolution also includes an alternative climate evolution with an anthropogenically increased greenhouse effect.

6.2.1 Shoreline displacement

During the last ice age, Sweden was covered by thick ice sheets. Large quantities of water were bound in the ice sheets, which had a maximum thickness above Scandinavia of around three kilometres /SKB 2006d/. When the ice melted the land mass was unloaded, which changed its level, and at the same time the level of the surrounding sea. The net effect of land uplift and sea level changed is called shoreline displacement (or migration).

Shoreline displacement and the processes it initiates, such as lake formation and terrestrialization, are among the most important changes expected to occur in the immediate future in the surface ecosystem around the repository. An algorithm for the process of shoreline displacement has been presented by /Påsse 1997/. Parameter values have been estimated from measurements in the Forsmark area /Hedenström and Risberg 2003/ in order to calculate future shoreline displacement. The calculated shoreline displacement is presented in Figure 6-1.This shoreline displacement was also used in the SR-Can safety assessment.

As a result of shoreline displacement, the shoreline will lie above SFR 1 in about a thousand years.

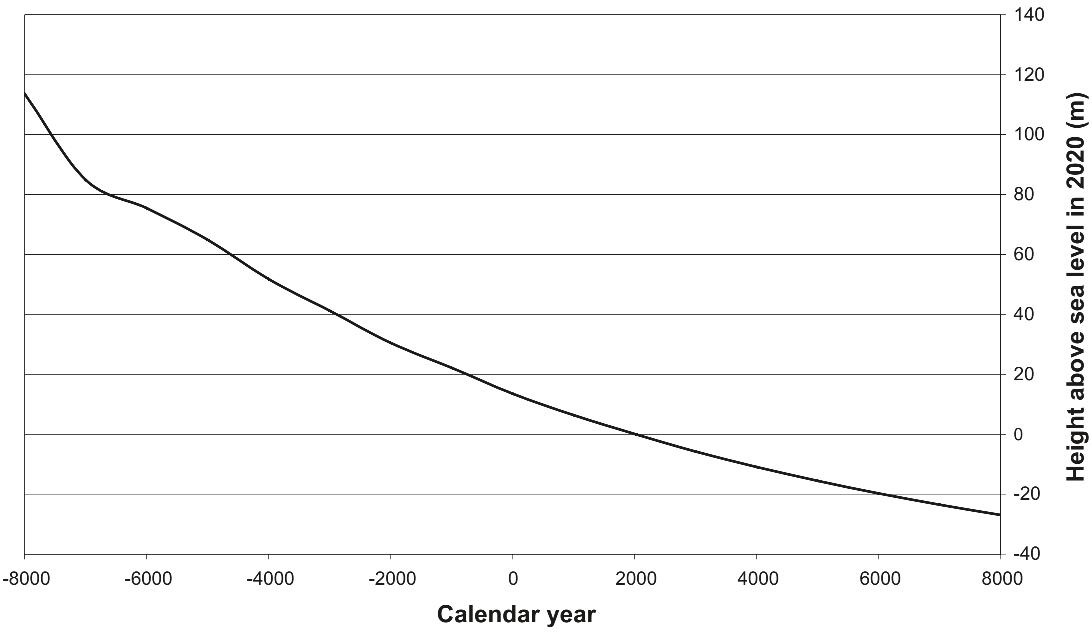


Figure 6-1. Calculated shoreline displacement for the Forsmark area from 8,000 BC to 8,000 AD, based on algorithms for shoreline displacement according to /Påsse 1997/ with parameter values from /Hedenström and Risberg 2003/.

6.2.2 Climate change

The following description of the evolution of the climate is a summary of a description done as a supplement to the SAFE project /Vidstrand et al. 2007/. The supplement is in turn based on the climate report from the most recent safety assessment for the final repository for spent nuclear fuel, SR-Can /SKB 2006d/.

Climate evolution far in the future cannot be predicted with today's knowledge. It is difficult to describe a particular evolution that can be said to be the most probable. On the other hand, it is very probable that the area above SFR 1 will undergo periods of different climate domains, and all transitions between them. Three relevant climate domains have been identified for the site and assessment period in question /SKB 2006d/:

- Temperate domain
- Permafrost domain
- Glacial domain

The temperature domain is defined as prevailing in regions without permafrost or ice sheets. It is dominated by a temperate climate in a broad sense, with cold winters and either warm or cold summers. Precipitation occurs throughout the year, as either rain or snow. The temperate domain has the warmest climate of the three climate domains.

The permafrost domain is defined as prevailing in regions with permafrost but without an ice sheet. Permafrost is in turn defined as land where the temperature remains at or below 0°C for at least two years in a row. How deep the permafrost can grow is a function of such factors as the heat balance at the ground surface, the thermal properties of the rock, the nature of the ground surface and the geothermal gradient. The permafrost domain has a cold climate, colder than the temperate domain, but warmer than periods with a glacial domain. Precipitation can occur in the form of snow or rain /French 2007/.

The glacial domain is defined as a region covered by an ice sheet. The glacial domain has the coldest climate of the three climate domains. Precipitation normally falls as snow. For a more detailed description of climate domains, see /SKB 2006d, Vidstrand et al. 2007/.

The reference evolution is based on reconstructed conditions for the past 120,000 years, i.e. for the latest glacial cycle with the Weichselian glaciation. The reconstruction has been done for the past 120,000 years, but this safety assessment only covers the first 100,000 years. The reasons for studying 100,000 years are given in section 2.3.2. The reference evolution is therefore only described for 100,000 years. The reference evolution also includes an alternative climate evolution with an anthropogenically increased greenhouse effect. Both of these are described below.

Climate evolution based on the latest glacial cycle

A climate evolution based on a reconstruction of the conditions at Forsmark during the latest glacial cycle, including the Weichselian glaciation, is illustrated in Figure 6-2. The reconstruction has been arrived at with the aid of simulations of ice sheet dynamics, isostasy and permafrost growth for the past 120,000 years. Descriptions of these simulations are found in SR-Can's climate report /SKB 2006d/. The reconstruction described for the Forsmark area applies to a great extent to SFR 1. The calculation of permafrost depth is based on properties of the rock on the envisioned site for a final repository for spent nuclear fuel. The siting of the repository determines when water-covered conditions prevail. The ground surface above SFR 1 is located today and for the next 1,000 years beneath the sea, unlike the repository in the SR-Can safety assessment. The permafrost depths reported in this report are calculated without heat input from a KBS-3 repository for spent nuclear fuel.

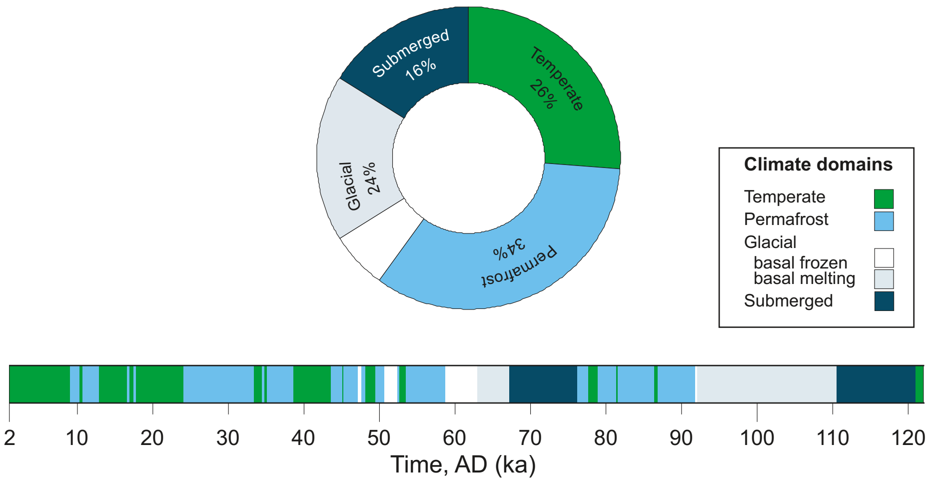


Figure 6-2. *Climate domains for the reference evolution based on reconstructed conditions at Forsmark for the latest glacial cycle /SKB 2006d/. The upper figure shows how large a fraction of the studied time is represented by the various climate domains. By basal frozen (cold-based) is meant that the lowermost parts of the ice sheet are frozen to the bed, and that no meltwater is produced, while basal melting (warm-based) means that the lowermost part is at the pressure melting point, and meltwater is generated by the ice. Note that the surface above the repository lies beneath the sea for the first thousand years, which is not evident from the figure.*

This climate evolution starts with a period of temperate climatic conditions that lasts for 8,000 years, of which roughly the first 1,000 years are under water for SFR 1. This is followed by alternating periods of periglacial and temperate climate domains. During the glacial cycle the climate goes gradually towards colder conditions, which is reflected in longer periglacial periods and shorter temperate periods as time passes. Ice covers the site on two main occasions during the glaciation, see Figure 6-3. During most of the time the ice sheet covers the site the ice is basal melting (warm-based), i.e. unfrozen conditions prevail in the transition zone between ice and bed, providing conditions for groundwater recharge. After the two glacial periods the site is isostatically depressed beneath the surface of the sea after the ice has left the area. For SFR 1, which is under water today, these periods will be slightly longer than is shown in Figure 6-2, which applies to the proposed site at Forsmark for a final repository for spent nuclear fuel. The time between these glaciations is dominated by periglacial conditions with permafrost. The maximum thickness of the ice sheet is about three kilometres. For more detailed information on this climate evolution see SR-Can's climate report /SKB 2006d/.

The evolution in Figure 6-2 and Figure 6-3 is not a prediction of future conditions but a relevant example of how climate and climate-related parameters covary during a glacial cycle /SKB 2006d/.

Climate evolution with increased greenhouse effect

This climate evolution describes conditions that include human-induced climate change according to, for example, /IPCC 2001, 2007, BIOCLIM 2004/, mainly by emissions of greenhouse gases. Both the global mean temperature and the temperature in Sweden are increasing due to an increased greenhouse effect. A temperate climate domain is assumed to prevail during the first 50,000 years, followed by the first mild period of climate evolution based on the reconstruction of the Weichselian, Figure 6-4. The reconstruction in Figure 6-4 was done for the proposed siting of the final repository for spent nuclear fuel in the Forsmark area. The difference compared with the site for SFR 1 is that SFR 1 initially, and for the next thousand years, lies under water. It is assumed that the start of the next ice age will be delayed, which means that

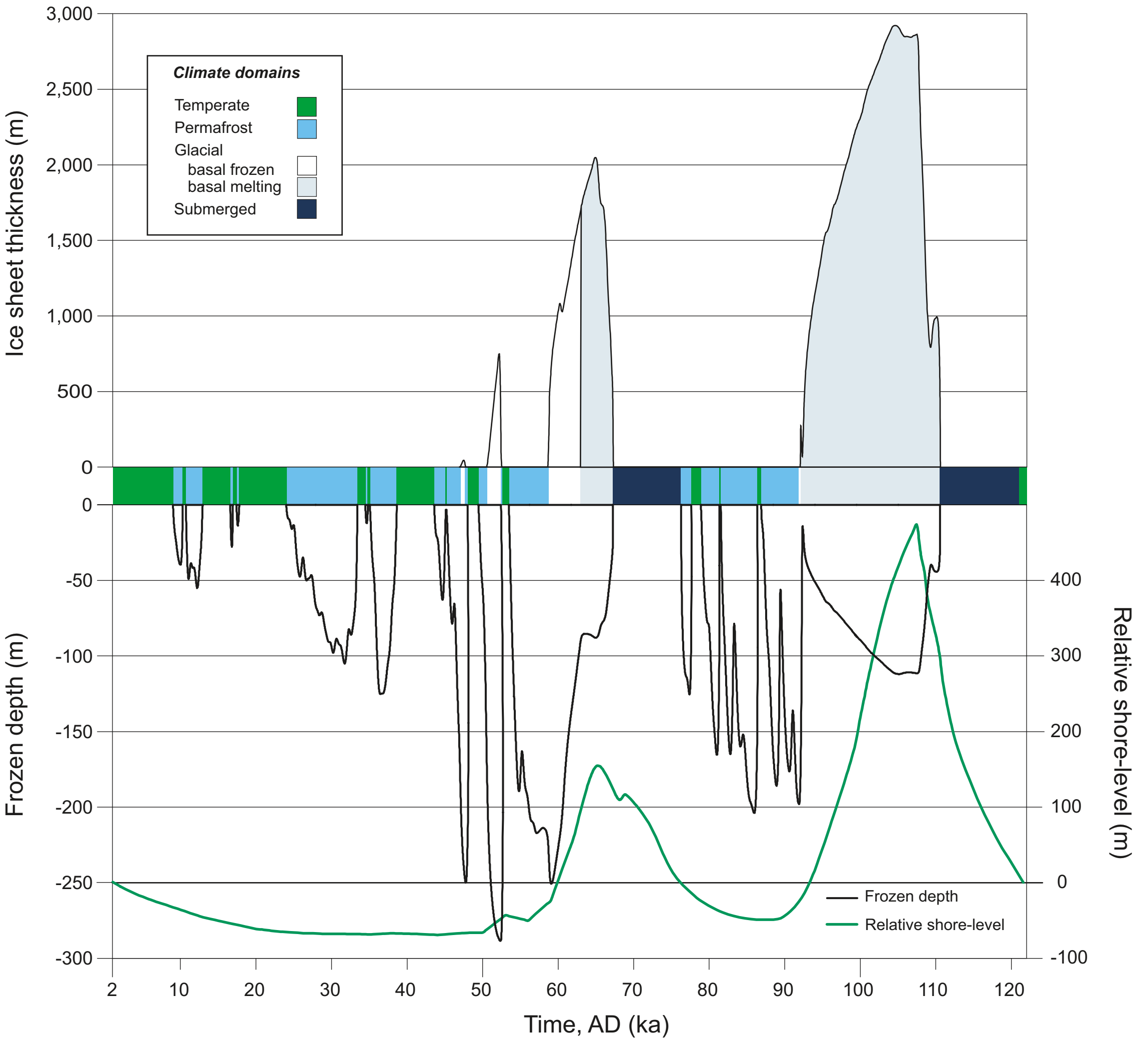


Figure 6-3. *Evolution of ice sheet, permafrost depth and relative shoreline displacement (relative to today's shoreline) for the reference evolution based on reconstructed conditions at Forsmark for the latest glacial cycle, modified from /SKB 2006d/. By basal frozen (cold-based) is meant that the lowermost parts of the ice sheet are frozen to the bed, and that no meltwater is produced, while basal melting (warm-based) means that the lowermost part is at the pressure melting point, and meltwater is generated by the ice. Note that the surface above the repository lies beneath the sea during the first thousand years, which is not evident from the figure.*

the glaciation periods will be shorter than in the climate evolution based on the repetition of the Weichselian glaciation. A total melting of the Greenland ice sheet is also assumed, which leads to a sea level rise. According to the isostatic modellings reported in SR-Can's climate report /SKB 2006d/, however, land uplift (isostatic rebound) is great enough to compensate for the sea level rise. The uncertainty in the reported shoreline displacement is relatively great, however. Shoreline displacement takes place in this variant of the climate evolution as well, but it is less than in the climate evolution based on the latest glacial cycle.

In summary, this results in an evolution that begins with 70,000 years of temperate climatic conditions, with the first short periods of periglacial conditions coming after around 60,000 years. Periglacial periods with heavy permafrost start after about 75,000 years. The first glacial period with an ice sheet above SFR 1 occurs after around 100,000 years. The evolution of the ice

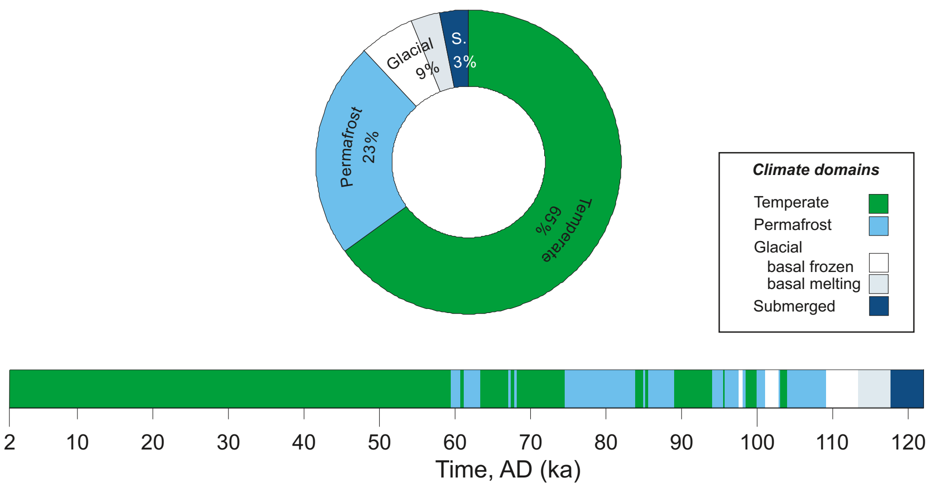


Figure 6-4. *Climate domains at Forsmark for the reference evolution with an anthropogenically influenced climate with increased greenhouse effect /SKB 2006d/. The upper figure shows how large a fraction of the studied time is represented by the various climate domains. By basal frozen (cold-based) is meant that the lowermost parts of the ice sheet are frozen to the bed, and that no meltwater is produced, while basal melting (warm-based) means that the lowermost part is at the pressure melting point, and meltwater is generated by the ice. Note that the surface above the repository lies beneath the sea during the first thousand years, which is not evident from the figure.*

sheet, permafrost and shoreline displacement is shown in Figure 6-5. The climate evolution in the variant with increased greenhouse effect should not be regarded as a prediction of what the future will look like with an increased greenhouse effect. The initial temperate period could be either shorter or longer than is described in this variant. More detailed information on this climate evolution, and the simulations done to arrive at it, can be found in SR-Can's climate report /SKB 2006d/.

6.3 Evolution of the surface ecosystem

The conditions in the surface ecosystem vary in time depending on the influence of changed climatic conditions. Initially, however, the main influence is from shoreline displacement (land uplift) and the processes it initiates, such as lake formation and terrestrialization of the nearby coastal area.

The description of the evolution of the surface ecosystem is divided into three main periods:

- The first 1,000 years after closure, which are mainly affected by the ongoing process of shoreline displacement.
- The period from 3,000 AD to 12,000 AD, which is largely affected by the ongoing process of shoreline displacement, but where the evolution of the climate plays a growing role with time.
- The period from 12,000 AD until around 100,000 AD, which is largely controlled by the evolution of the climate. The description is therefore based on the two alternative climate evolutions described in section 6.2.2.

The result of the past shoreline displacement when the Forsmark area rose above the sea and the consequences of the future redistribution of the proportions of sea and land in Öregrundsgrepen and in the area immediately above SFR 1 have been modelled and are illustrated in a background report to SR-Can's safety assessment /SKB 2006b/. Based on GIS (Geographic

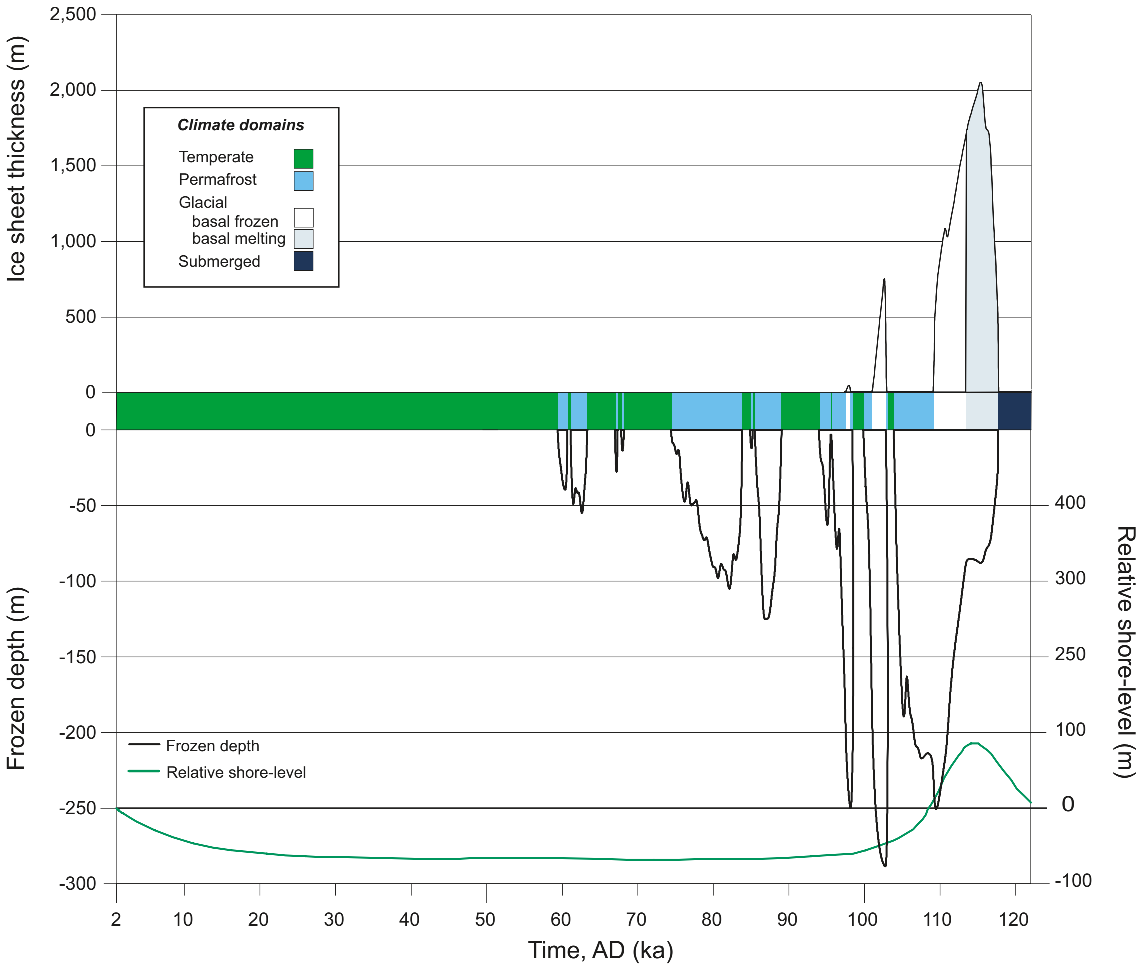


Figure 6-5. Evolution of ice sheet, permafrost depth and relative shoreline displacement (relative to today's shoreline) for the reference evolution's alternative with greenhouse effect for Forsmark, modified from /SKB 2006d/. By basal frozen (cold-based) is meant that the lowermost parts of the ice sheet are frozen to the bed, and that no meltwater is produced, while basal melting (warm-based) means that the lowermost part is at the pressure melting point, and meltwater is generated by the ice. Note that the surface above the repository lies beneath the sea during the first thousand years, which is not evident from the figure.

Information System), in which detailed information from models of shoreline displacement, hydrology and the terrestrial area has been collected, the landscape at the Forsmark area has been described with the aid of biosphere objects such as lakes, coastal basins, mires etc. These biosphere objects are interconnected via water flows. Provided the current climate will prevail in the future, forecasts have been made in steps of 1,000 years of the change of the objects with time. From these studies, relevant information has been obtained regarding those objects that are affected by calculated releases from SFR 1.

Calculations of the future formation of lakes in Öregrundsgrepen were made in the SAFE project /Brydsten 1999b/. An inner model area, the SAFE area, situated immediately above SFR 1, was selected on the basis of the area's bottom topography as an expected future sub-catchment, see Figure 6-6. This area, hereinafter called the SAFE Basin, is in direct contact with several basins within Öregrundsgrepen. Calculations have shown that the SAFE Basin is the initial discharge area for groundwater that has passed through the repository parts /Holmén and Stigsson 2001a/.

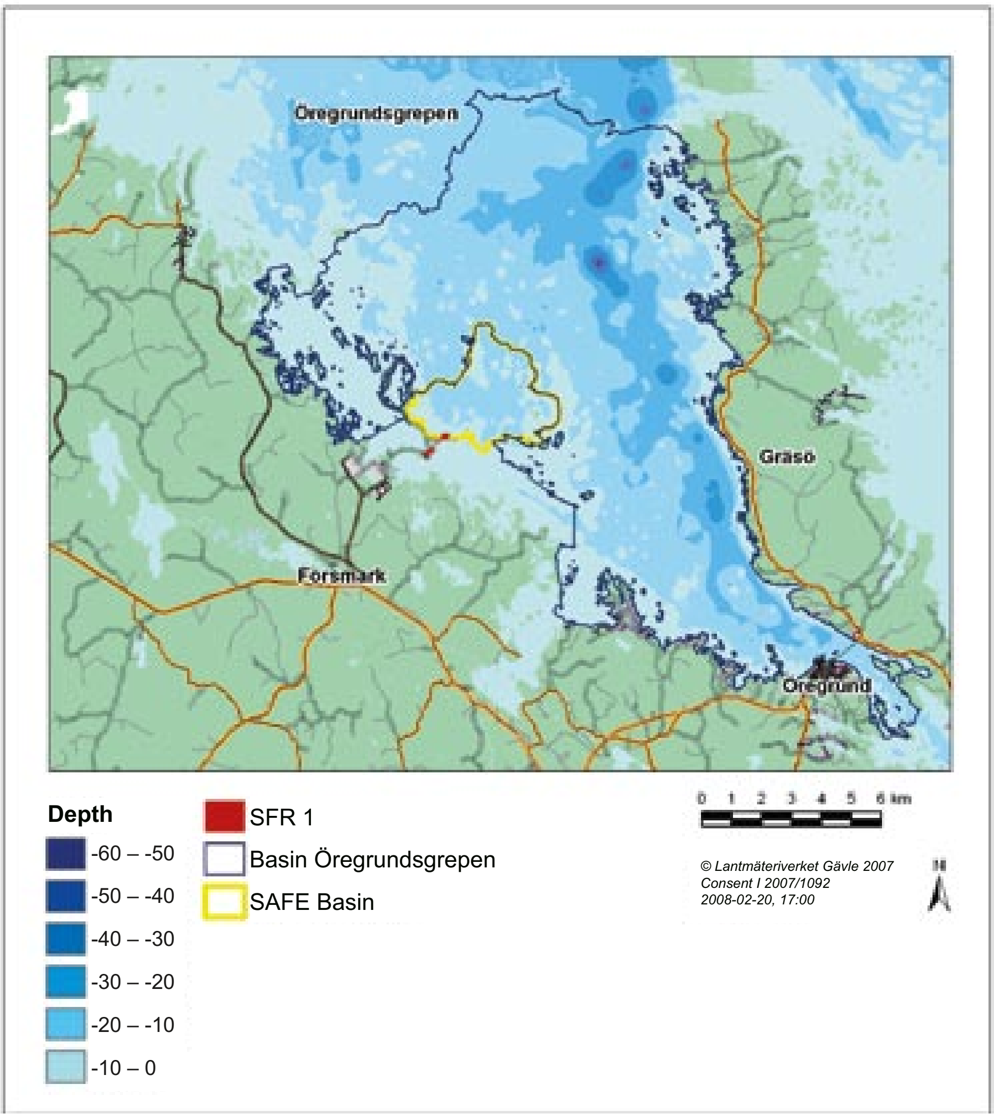


Figure 6-6. *Öregrundsgrepen with the inner model area, the SAFE basin, marked by yellow line. The outer model area comprises Öregrundsgrepen, based on /SKB 2006b/.*

Detailed information on the Forsmark area with a focus on descriptive models of present-day terrestrial and limnic ecosystems and quantification of carbon turnovers is documented in /Lindborg 2005/. Much information has been taken from this report with regard to forecasts for the Forsmark area assuming that future conditions are similar to current ones, a method that was also used in the safety assessment for SR-Can.

As a result of shoreline displacement, new islands and enclosed archipelagos are formed from the present-day basins in Öregrundsgrepen. This leads to changes in the sedimentation conditions. Shallow exposed areas are left dry and the sediments are eroded, while a larger portion of shores are protected against extensive erosion in the archipelago that is formed. The calmer water allows increased sedimentation /Brydsten 1999a/. The archipelago that is formed reduces water turnover in the area /Engqvist and Andrejev 2000/. The decrease in depth and water exchange causes a shift in the marine plant and animal communities towards a larger proportion of plants /Kumblad 2001/, but the total quantity of living organisms also decreases due to a decrease in the water volumes and the bottom surface area.

Figure 6-7 below shows how a marine basin in Öregrundsgrepen can be affected by shoreline displacement (land uplift) and terrestrialization.

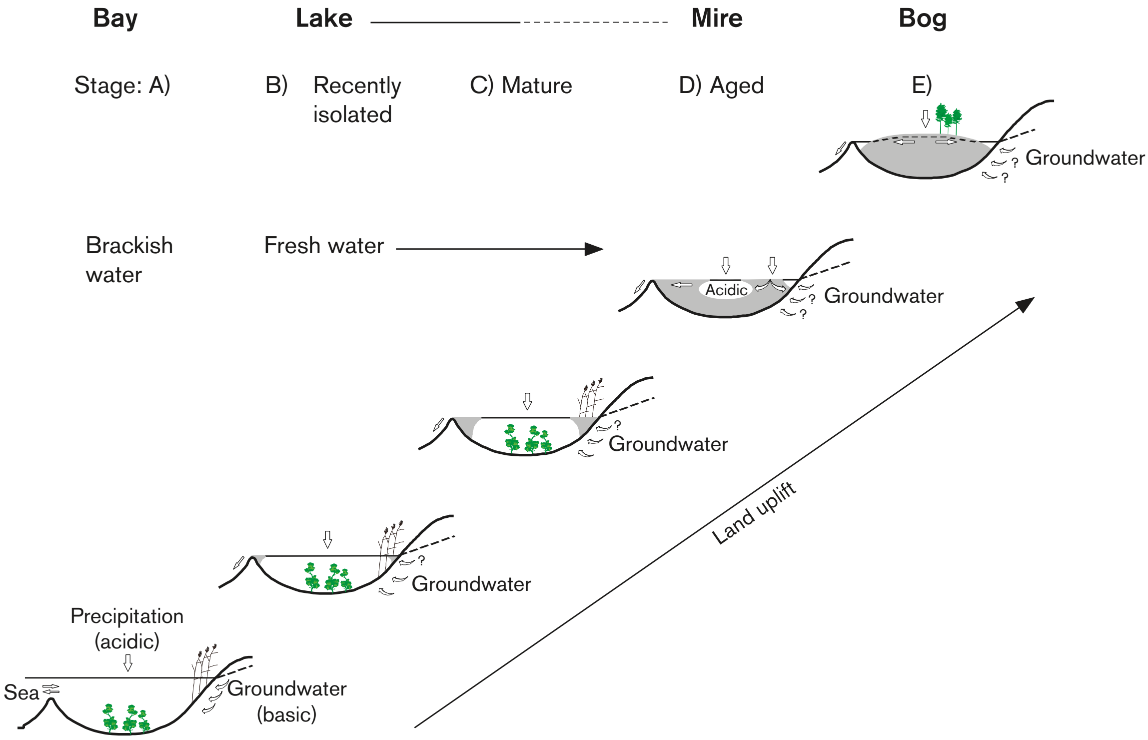


Figure 6-7. *Suggested ontogeny with isolation and terrestrialization of future lakes in the area above SFR 1 /Brunberg and Blomqvist 2000/.*

6.3.1 The next 1,000 years

According to the climate evolution based on the latest glacial cycle with today's prevailing climate domain, the ongoing shoreline displacement will continue for the next 1,000 years, see Figure 6-8.

The marine area will change during the coming 1,000 years as present-day near-shore bottoms are transformed into land vegetated with herbaceous plants, grass and trees in sheltered areas, while rock outcrops and boulders dominate the areas exposed to wind and water /SKB 2006a/. Lakes have been formed along the former shoreline /Brydsten 2006/. The area above SFR 1 is, however, still a coastal area, with reduced water area, depth and volume and with sparse near-shore vegetation due to exposure to wind and water.

In the SAFE Basin, the area immediately above SFR 1, the water area decreases by about 20% and the maximum depth is around six metres shallower at the end of the period /Kautsky 2001/. This can cause a small reduction in the high water turnover. The proportion of accumulation bottoms increases from just over 20% to just over 40%, mainly due to the fact that the eroded areas decrease as shoreline displacement proceeds /Brydsten 1999a/.

The decrease in depth (shoaling) results in a decrease in total biomass in the area, but this change is judged to be marginal. Studies of the model area have predicted that by 4,000 AD the amount of biomass will have decreased by 20% from the present-day level /Kumblad 2001/.

More recent investigations of the area in conjunction with the site investigations for siting of a final repository have not given cause for any changes in the conclusions that were drawn in the SAFE study.

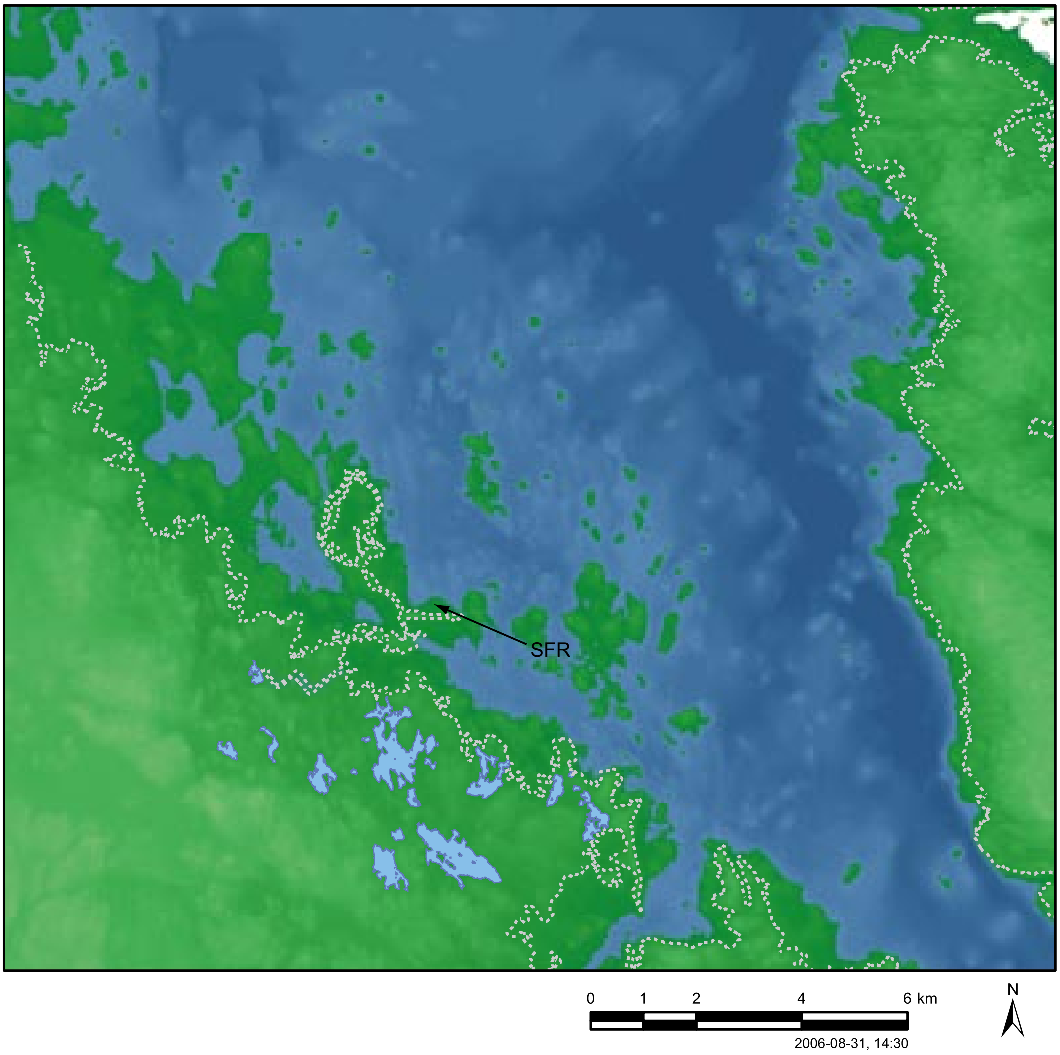


***Figure 6-8.** Expected coastline at Forsmark in 1,000 years with today's climate still prevailing (no greenhouse effect). The dashed line shows today's coastline. The lighter green colour indicates higher land areas while the darker blue indicates greater water depths /SKB 2006a/.*

Hydrogeological modelling shows that discharge areas for the groundwater that has passed through the repository will be on the sea floor during most of the period /Holmén and Stigsson 2001a/, see also section 6.4.2. At the end of the period, when the shoreline lies above the repository, the discharge area is the coastal area situated directly above the repository, see Figure 6-9. After the shoreline has passed the repository, the discharge areas gradually move outward to sea.

6.3.2 The period from 3,000 AD to 12,000 AD

In the following description the period from 3,000 AD to 12,000 AD is divided into three sub-periods: the archipelago period, the lake period and the land period, depending on the evolution of the area as a result of shoreline displacement.

The archipelago period: 3,000 AD to 4,900 AD

As a result of continued shoreline displacement, the calculated discharge areas increasingly end up on land (Figure 6-27), where vegetation can begin to grow. No agricultural activities to speak of can be expected, however, due to the high incidence of boulders and stones /Elhammer and Sandkvist 2005/.

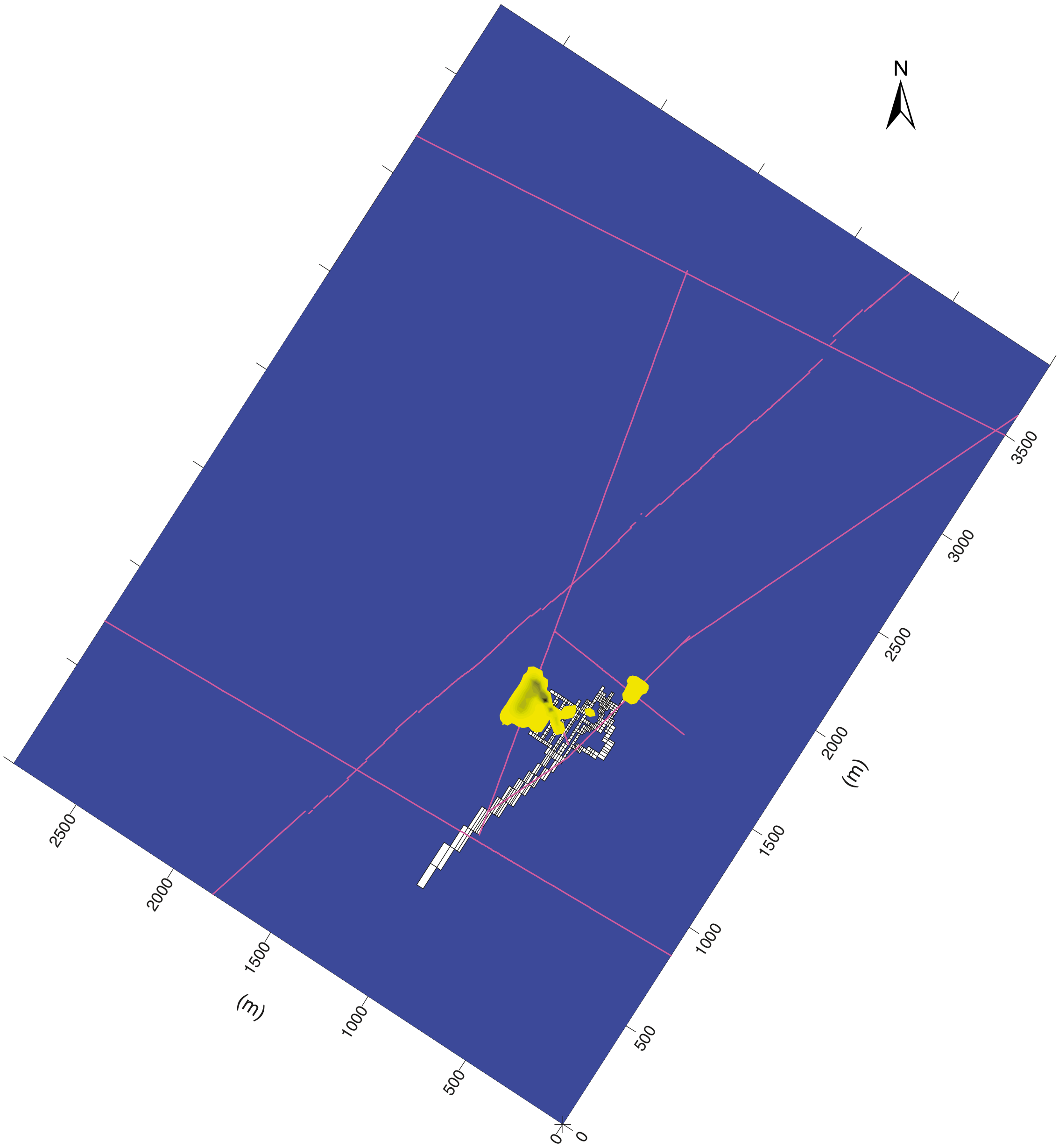


Figure 6-9. *Predicted discharge areas for water flows from the silo and the rock vaults after the shoreline has passed the repository (3,000 AD) /Holmén and Stigsson 2001a/. The yellow areas mark the location of the discharge areas. The repository with access ramp is marked with small squares and the fracture zones are pink.*

An archipelago rich in islands is formed, where bays are pinched off at the end of the period to isolate lakes. The marine area immediately above SFR 1 shrinks, so that the sea surface area in 4,000 AD is roughly half of what it is today /Brydsten 1999b/. In the SAFE Basin, the area immediately above SFR 1, the water volume declines by 90%, while the water retention time increases to around 13 days from a current retention time of less than one day /Engqvist and Andrejev 2000/. The southern straight in Öregrundsgrepen is closed at around 3,000 AD, and the retention time in Öregrundsgrepen is just below twice as long at 4,000 AD as it is today /Engqvist and Andrejev 2000/.

The proportion of shallow sunlit bottoms increases, since land uplift causes the water depth to decrease, which affects the distribution of plant and animal communities in the basin /Kumblad 2001/. The total quantity of biomass decreases by about 20%, but the proportion of bottom fauna and their grazers increases by 60%, while benthic fauna on soft bottoms are reduced by 50–80%. Pelagic plankton are reduced to half, though the species composition is not expected to change /Kautsky 2001/.

The turnover of matter is also changed. The increase in bottom flora results in an increase in the total primary production by about 10%, whereas decomposition is reduced to half /Kumblad 2001/. This means that the mass balance in 4,000 AD gives twice as great a surplus of organic material compared with 2,000 AD. The turnover of particulate and dissolved organic carbon in the water is reduced considerably to about 20% of the turnover in 2,000 AD. In order for the mass balance to be correct, increased sedimentation and fixing of organic material in the sediments is then required /Kautsky 2001/. Altogether, this means that the retention of matter in the sea is higher in 4,000 AD than in 2,000 AD.

The proportion of land areas will increase in the former marine area to half of the area of the SAFE Basin, i.e. to about 6 km^2 /Kumblad 2001/. In general, deciduous forest will initially develop in the near-shore areas, and with time coniferous forests will increase as the ground becomes drier /Jerling et al. 2001/. In the lower areas, lakes will be formed by isolation, but since most of them are shallow they will quickly become silted-up and turn into mires /Brunberg and Blomqvist 2000/. Brydsten has developed a model for terrestrialization of lakes in areas with positive shoreline displacement /Brydsten 2004/. The model showed that the size of the lakes was strongly related to the time for terrestrialization, so that small lakes became filled with sediments and vegetation more quickly. Mires eventually develop into forested wetlands. Since the sediment and peat layers will be thin and the ground will have a large number of boulders, they will probably not be drained for cultivation /Jerling et al. 2001/.

Model studies of the Forsmark area's hydrology, water balance and transport mechanisms /Vikström and Gustafsson 2006/ have shown that the hydrological conditions may change in conjunction with peat development so that former discharge areas may become recharge areas. This supports the results of Holmén and Stigsson /Holmén and Stigsson 2001a/, where it is shown that the discharge area follows the shoreline and that most of the discharging water will run out into the sea and the future archipelago.

Only after the shoreline has passed the repository, after 3,000 AD, can wells be drilled directly into the repository. Wells are assumed to be drilled as shoreline displacement proceeds and with the same density as that in the Forsmark area today /Kautsky 2001/. It is therefore probable that after another 1,000 years wells may be drilled in the repository's discharge area. From an exposure viewpoint, the water capacity of the wells is a very important parameter. A study of well capacities in wells situated within the Forsmark area shows that wells east of the Singö Zone, where SFR 1 is located, generally have capacities averaging 1.2 m^3 per hour /Gentzschein et al. 2006/, see section 4.7.3.

The lake period: 4,900 AD to 7,500 AD

Around 4,900 AD, several sea bays are isolated and become lakes in the present-day Öregrundsgrepen near SFR 1 (Figure 6-10). Lakes form in the SAFE Basin, the largest being 1.6 km^2 with an average depth of 1.4 m and a maximum depth of 4.8 m /Brydsten 2006/.The lake is deep enough so that the infilling process will proceed slowly for the next 2,000–3,000 years. The transition to fresh water results in great changes in retention times, chemical properties and ecosystem structure.

The retention time (water renewal time) in the lake is dependent on the size of the catchment and the runoff and is calculated to be 89 days, assuming today's precipitation /Brunberg and Blomqvist 2000/. The catchment is relatively small and no major watercourses are expected to discharge into the lake, since the Olandsån and Forsmarksån rivers are assumed to run through the lake system further east /Brydsten 1999b/.

Figure 6-10. *Present and future lakes that will have formed some time before 9,000 AD in the Forsmark area. By 9,000 AD, however, most of the lakes will have dried up and grown over /Brydsten 2006/.*

The lake is expected to become an oligotrophic hardwater lake, like existing lakes that have similar catchments and morphometry /Brunberg and Blomqvist 2000/. The lake's high alkalinity is due to the alkaline groundwater, which has been affected by the limestone in Gävlebukten. The oligotrophic hardwater lakes in this area are characterized by rapid sedimentation growth with "algal gyttja" and clear, hard water. This means that the lake can be an attractive source of drinking water and have favourable fish production, but not large numbers of fish due to the small size of the lake. Brydsten has shown that the length of the lacustrine phase (the time from the formation of a lake until it is completely filled) is about 3,000–4,000 years for the smaller lakes /Brydsten 2004/. As in the premises for the SR-Can safety assessment, it is further assumed that most of the lake has been transformed into a mire by around 7,000 AD /SKB 2006b/. It is conceivable that the lake is of interest for drainage, since it is probably the only place in the area where the sediments can become thick enough to be arable. If the lake is drained, peat continues to grow.

Any radionuclides that have left the repository will have passed through the lake's present-day bottom or within the lake's catchment. It is also probable that discharge will take place in the lake during some period (see further section 6.5.2). This means that the lake bottom can potentially accumulate radionuclides both when discharge has occurred through it and due to the fact that eroded contaminated material at previous discharge points has resedimented in the former sea bay that later formed the lake.

Changes of the terrestrial vegetation in the former SAFE Basin will be moderate during this period, since the distance to the current shoreline has become considerably longer. The shoreline at 7,000 AD is expected to be near the island of Gräsö /SKB 2006a/. A succession from the previous deciduous vegetation on the shores to a more coniferous vegetation is expected /Jerling et al. 2001/. No agricultural activities to speak of can be expected in the former SAFE Basin, however, due to the high incidence of boulders and stones /Elhammer and Sandkvist 2005/.

Wells may be drilled in the area with a density estimated to be the same as today's, which means around 0.5 well per km^2 /Kautsky 2001/. On the other hand, the formed lake is probably an attractive source of water, so it is possible that the frequency of wells may be lower. In all probability, the area resembles what can be found a kilometre or so inland today from Forsmark, with a sparse population and a low density of wells (see Chapter 4).

The land period: 7,500 AD to 12,000 AD

After 7,500 AD, the whole former Öregrundsgrepen is expected to have become a terrestrial area with several large, deep lakes along Gräsö. The lake formed in the former SAFE Basin is expected to have been filled in or drained. The only part of the former basin with the potential to be cultivated is probably the former lake bed, since it is only there that sufficiently thick sediment layers could have formed. The rest of the area is dominated by forest and mire land in accordance with the premises for future changes that were used for the SR-Can safety assessment /SKB 2006b/.

The terrestrial vegetation will naturally be dominated by trees, and with time will have an increasing coniferous character.

During this period a transition to a colder climate is also expected, according to the reference evolution for the climate based on the latest glacial cycle (see section 6.2.2), which has consequences for the terrestrial vegetation.

6.3.3 The period from 12,000 AD until around 100,000 AD

During the period from 12,000 AD until around 100,000 AD, the evolution of the surface ecosystem is controlled by the climate evolution. The evolution of the surface ecosystem is described below for the two variants of the climate evolution described in section 6.2.2.

The evolution of the surface ecosystem with climate change based on the latest glacial cycle

The following section gives an example of a reasonable evolution of the surface ecosystem at Forsmark up until 100,000 AD, based on a reconstruction of the most recent ice age, which has been selected as the reference evolution for the climate (see section 6.2.2). Up until permafrost conditions appear, forest and mire land is assumed to dominate the area.

During periods with a permafrost domain, tundra conditions prevail at Forsmark. Tundra conditions are characterized by low precipitation, wind, long cold winters and a short growing period /French 2007/. The average temperature during the three growth months is generally lower than 10°C, and the ground is usually snow-covered for the rest of the year. During the summer the uppermost part of the land surface thaws, but there is no infiltration due to the permafrost /French 2007/. Owing to the appearance of the area, e.g. its topography, mire/fen areas with sedges may form, since the water cannot infiltrate. Peat production is low, however. The constant wind and the frozen ground make it difficult for large trees to grow, and the vegetation is dominated by dwarf birch, shrubs and grass, which are protected by the snow cover in the winter /Oliver 2005/. This vegetation has developed extensive root systems to survive harsh conditions /Oliver 2005/. The underlying soil in the Forsmark area is currently relatively calcareous, so a species-rich flora can develop during the summer months providing the glaciations have not altered these conditions. Plant production is low /Oliver 2005/.

The animal life under tundra conditions consists primarily of small mammals/rodents, shorebirds and herds of musk oxen and domesticated or wild reindeer /Oliver 2005/. The reindeer seek warmer areas in the winter, the birds migrate while the small rodents have adapted to the environment by overwintering beneath the snow. Larger animals such as musk oxen can endure the harsh climate thanks to their heavy fur /Oliver 2005/.

The conditions described above have a great bearing on possible exposure to radionuclides from the repository. If the ground is frozen all the time, there can be no outward transport of radionuclides. Radionuclides could reach the surface ecosystem if there are taliks in the area. Taliks are unfrozen zones that are normally associated with extensive discharge areas, such as large lakes /SKB 2006d/.

The low primary production /Oliver 2005/ entails poor conditions for food production in the area, which should limit human settlement. The best conditions for settlement are in the above-mentioned talik areas. Formation of talik areas cannot be ruled out, and if this happens it can happen in connection with the deep snow formed due to shoreline displacement, west of Gräsö. The probability of humans being exposed to radionuclides from the repository can, however, be regarded as very low.

During the glacial periods the area is covered by an ice sheet. During the periglacial periods, however, there may be a productive marine ecosystem that can be utilized by humans and animals at the margin of the ice cap. The probability of permanent settlement must, however, be considered low due to the harsh conditions. Nevertheless, there are populations today, such as Inuit, that live under similar conditions and make a living from hunting and fishing. So such an evolution could be possible. However, the marine influence means both large water volumes and a high water turnover.

The evolution of the surface ecosystem in connection with climate change with increased greenhouse effect

According to the greenhouse variant of the reference evolution for the climate (see section 6.2.2), the warm temperate climate will persist for a very long time, up until 50,000 AD, before the onset of the glacial cycle described above. This scenario is based on the results of international projects /IPCC 2001, 2007, BIOCLIM 2004/, which suggest that ice-free temperate conditions could prevail in Sweden for a long time before the next permafrost period is expected. The average temperature will rise by about 2–3°C during the summer period, and the winters will also be milder than today at Forsmark /BIOCLIM 2004, Rummukainen 2003/. Precipitation is also expected to increase /SKB 2006a, p. 378/. Shoreline displacement continues in this variant as well /SKB 2006a, p. 375/, but there are great uncertainties. The shoreline level may remain constant or even rise. The increased precipitation may increase runoff if it is not offset by increased evaporation /SKB 2006a/. If runoff to the Baltic Sea increases, the salinity of the Baltic Sea may decrease, since it is dependent on the input of fresh water /Gustafsson 2004a, 2004b/.

A warmer climate could theoretically also lead to the onset of permafrost conditions in the Forsmark area before 50,000 AD. This could occur if the general temperature increase reduces the thermohaline circulation in the North Atlantic so that less heat is transported to Scandinavia than now /SKB 2006d/. This possibility has low probability /IPCC 2007/, but is nevertheless covered by the scenario for early freezing of the repository (see section 7.6.2).

Due to ongoing process of isostatic land uplift, the area will be several kilometres from the coastline in 12,000 AD. Certain parts of the former Öregrundsgrepen may then have favourable conditions for growing food /SKB 2006b/, and limited agriculture can be expected.

6.3.4 Summary of the evolution of the surface ecosystem

In summary, the evolution of the surface ecosystem based on climate change in accordance with the latest glacial cycle may entail that the initial coastal area, as the recipient of radionuclides from the repository via a lake and a mire, becomes forested, as a result of shoreline displacement.

However, the possibility cannot be ruled out that former sediment can be used for agriculture, which means that accumulated activity can reach man. After the first ten thousand years the climate deteriorates. Tundra conditions create difficult conditions for settlement and food production, so it is assumed that exposure can only take place via a forest ecosystem. Later, under glacial conditions, the area is ice-covered and only the aquatic ecosystems can give any exposure. It is also the aquatic ecosystems that are of interest when the area is beneath the sea, which is to be expected after glaciations.

If, on the other hand, the climate should get warmer and temperate conditions prevail for extended periods, according to the alternative with increased greenhouse effect, certain areas (especially those that were formerly accumulation bottoms) may be used for agriculture, while the forest ecosystem is perhaps still the most likely. Both of these surface ecosystems are therefore studied when calculating dose.

6.4 The evolution of the repository during the first 1,000 years after closure

The evolution of the repository during the first thousand years is controlled by initial transient processes, which is an important reason why the first thousand years after closure has been chosen as one of the three periods for describing the reference evolution. This period also complies with the requirements in SSI FS 1998:1 regarding reporting of different time periods, where the first thousand years is pointed out with the requirement that the assessment of the repository's protective capability during this period shall be based on quantitative analyses of the effects on man and the environment.

The activity in the waste will decay so that after 1,000 years it is approximately 2% of the activity at closure. In the beginning the activity is dominated by the short-lived radionuclides Ni-63, Cs-137 and Co-60, but at 1,000 years after closure the activity consists mainly of inorganic C-14, Ni-59 and organic C-14.

Initially the Baltic Sea covers the area above SFR 1, but due to shoreline displacement the shoreline will be located above SFR 1 in about a thousand years, see section 6.2.1.

The current period with temperate climate can be expected to extend several thousand years ahead in time, see section 6.2.2.

6.4.1 Thermal evolution

The temperature of the repository will be determined almost entirely by the exchange of heat with the surrounding rock and groundwater. Heat transport can essentially be expected to take place via heat conduction and is governed by the thermal conductivity and heat capacity of the materials.

The impact of the repository on the temperature is negligible, since there are no significant heat-generating processes in SFR 1. Corrosion of aluminium could be an exception, but has been found to be of no importance /Moreno et al. 2001/.

During the first thousand years after closure, no change in climate is expected that would lead to freezing of the repository.

6.4.2 Hydrogeological evolution

The size, direction and distribution of the water flow in different parts of the repository system and the geosphere affect radionuclide transport. Transport of other species, microorganisms and bacteria is also controlled by the water flow. Owing to the importance of the water flow for radionuclide transport, low flow in the repository parts is one of the defined safety functions for the safety assessment (see Chapter 5).

The site of SFR 1 was chosen in part because it is located in an area with a limited hydraulic gradient and limited fracture transmissivity. The repository site was chosen in part for the purpose of ensuring low water flows through the different repository parts. The different repository parts have been designed with different capabilities for limiting the water flow. The silo has the most advanced design; all waste is conditioned, all waste packages are embedded in porous concrete, there is an internal compartment structure of concrete, the outer walls are made of thick concrete, and above all the concrete silo is surrounded by bentonite. All waste in BMA is also conditioned. BMA has a simpler concrete structure and is backfilled with gravel or sand, so that the water that flows into BMA will for the most part flow through the backfill instead of through the more watertight concrete structure. In 1BTF and 2BTF the concrete tanks are positioned so that they form an inner structure that is less permeable to water flow than the side and top fill of gravel or sand. BLA has no structure that limits the water flow through the waste.

Hydrogeological calculations are needed to quantify expected water flows in the different parts of the repository and to analyze the water flow from the repository to the surface ecosystem. The results constitute important input data for calculating radionuclide transport and dose.

Drainage pumping during the operating phase will cease when the repository has been closed. The hydrogeological model /Holmén and Stigsson 2001a/ has been used to calculate how long it takes to fill and saturate the repository with groundwater. The calculations show that the void (porosity) inside the silo repository is saturated last and that this can take 25 years. In a study of how freezing can affect the silo repository, the time for complete saturation of the bentonite surrounding the concrete silo has been estimated to be on the order of 100 years /Emborg et al. 2007/. These two studies shed light on the size of the uncertainty in the time for water saturation of the silo repository. It only takes a few years to fully saturate BMA, BLA and BTF.

Calculations /Stigsson et al. 1998/ show that the density effects resulting from salinity variations can be neglected, but that it is important to take shoreline displacement into consideration.

Hydrogeological model studies have been carried out in order to estimate the future ground-water flow at SFR 1, in the repository and in the surrounding rock /Holmén and Stigsson 2001a, Holmén 2005, 2007/. The first study comprises the foundation of the modelling and has been supplemented with uncertainty analyses of both the water flow through SFR 1 /Holmén 2005/ and the flow paths from the silo repository and the rock vaults /Holmén 2007/.

The hydrogeological models represent the repository and the surrounding rock mass at SFR 1 with regional fracture zones. The models that represent different-sized areas and different degrees of detail are termed *regional*, *local* and *detailed*.

The regional model encompasses a larger regional area whose outer boundaries have been selected on the basis of natural hydraulic boundary conditions. The regional model takes shoreline displacement into account, and the results are used as boundary conditions in the local model. The local model in turn provides boundary conditions for the detailed model.

The local and detailed models include a detailed description of the repository and the surrounding rock mass and fracture zones. The detailed model also contains the various structures inside the silo repository and the rock vaults.

Shoreline displacement follows an interpolation performed on the basis of data for Stockholm and Gävle presented in /Påsse 1996/, see also section 6.2.1. Compared with the level of today's shoreline, the shoreline at SFR 1 in 1,000 years will be six metres lower. As a result of shoreline displacement, the shoreline will lie above SFR 1 in about a thousand years.

The pattern of the water flow around SFR 1 has been simulated in the hydrogeological models. The flow paths from the repository to the ground surface have been analyzed with the aid of notional particles that are transported with the groundwater flow. Each particle path represents one possible flow path, and a large number of particle paths together show a distribution of flow paths. The flow paths start at the walls, floors and roofs of the silo repository and the rock vaults. The distribution of the starting points represents the variation in water flow at walls, floors and roofs. Thus, many flow paths start where the water flow is large while few start where the water flow is small. The flow paths only represent advective transport.

Regional groundwater flow and water flow in the silo repository and the rock vaults

The size and direction of the regional groundwater flow and the water flows in the silo repository and the rock vaults have been modelled primarily to enable advective radionuclide transport in the repository and the geosphere to be calculated.

The local model includes the entire repository system at SFR 1. In addition to the access ramp, the detailed model also includes the entire repository system, see Figure 6-11. The detailed model also includes the internal structures in the silo repository and the rock vaults. Generally speaking, the interior of the silo repository and the rock vaults consists of a volume where the waste is emplaced, together with surrounding barriers and backfill. In the silo repository and all rock vaults except BLA, the waste is placed in a hydraulic barrier. Figure 6-12 shows vertical cross-sections through the silo repository and the rock vaults as they are represented in the detailed model. In the calculations BLA is backfilled with a material that has a high permeability, but according to current plans BLA will not be backfilled, see section 4.2.4.

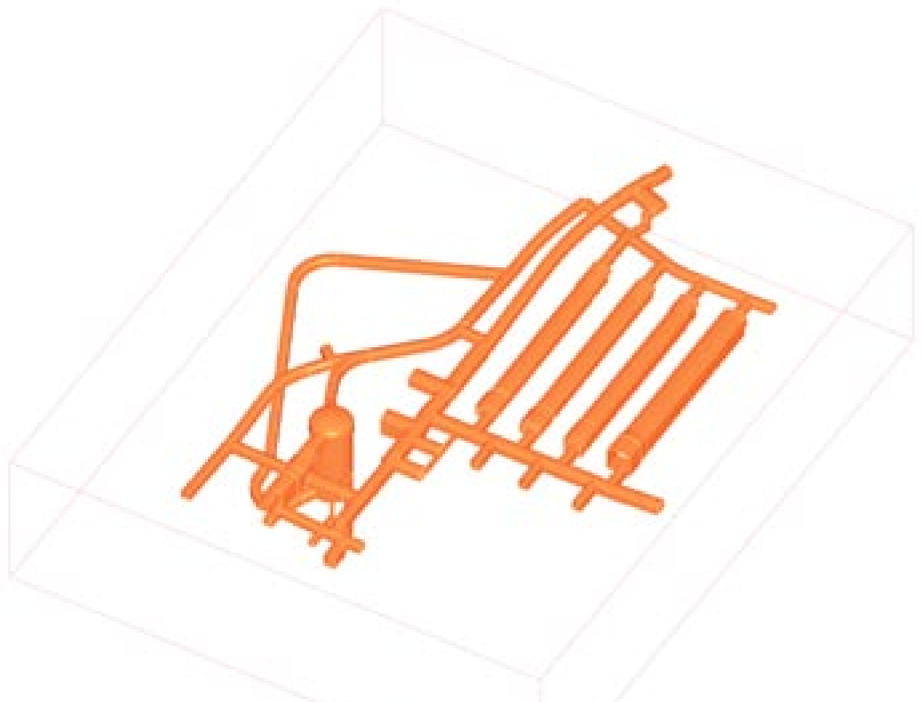


Figure 6-11. *Schematic illustration of the parts of the repository system that are represented in the detailed hydrogeological model /Holmén and Stigsson 2001a/.*

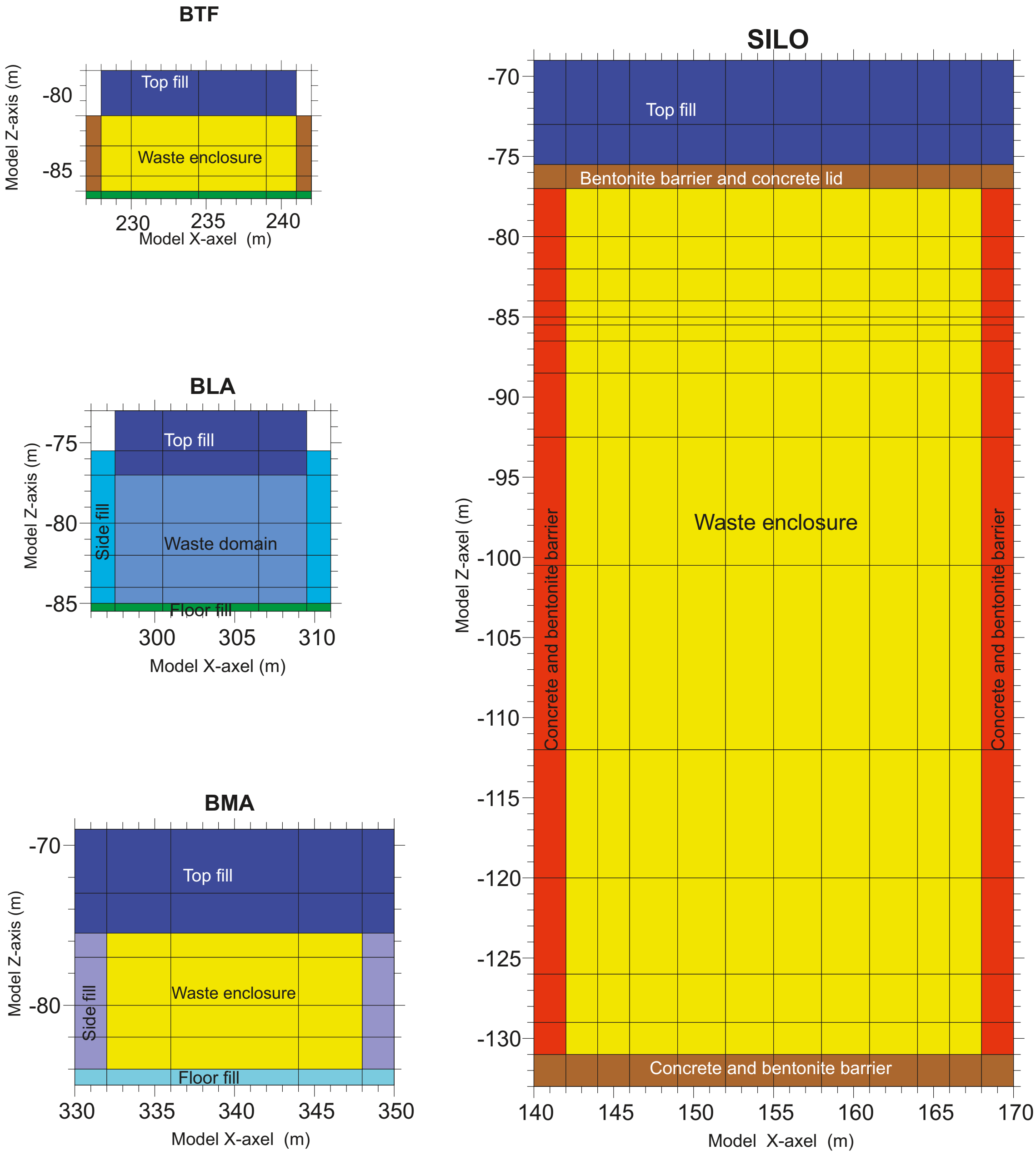


Figure 6-12. *Inner structures in the silo repository and the rock vaults as they are represented in the detailed hydrogeological model. Vertical cross-sections are shown. All figures are on the same scale. BTF, BLA and BMA have a horizontal extent of 160 m, while the silo repository is circular. Blue shades represent structures with high hydraulic conductivity, such as top fills. Yellow represents concrete enclosures, which have low conductivity. Red and brown represent barriers with low conductivity. Green represents the floors in BTF and BLA, which have a relatively low conductivity /Holmén and Stigsson 2001a/.*

The calculated water flows for BLA as a whole are not appreciably affected by this, due to the fact that the total groundwater flow through a tunnel is mainly determined by the permeability of the surrounding rock if the backfill material in the tunnel has a much greater permeability than the surrounding rock. The distribution of the flow inside BLA is, however, affected more by whether the calculations are done with or without backfill. If the calculations were done without backfill, the water would run past the waste domain to a greater extent and the flow through the waste domain would consequently be lower.

Table 6-1. Description of the inner structures in the silo repository and the different rock vaults in the detailed hydrogeological model as well as their hydraulic conductivity /Holmén and Stigsson 2001a/.

Structure	Hydraulic conductivity* (m/s)
1BTF and 2BTF	
Floor with relatively low permeability	$1{,}3 \cdot 10^{-8}$
Side fill with low permeability	$8{,}3 \cdot 10^{-9}$
Concrete enclosure with low permeability that contains the waste	$5.1 \cdot 10^{-9}$
Top fill with high permeability	$1 \cdot 10^{-5}$
Loading areas at tunnel ends with high permeability	$1 \cdot 10^{-5}$
BLA	
Floor with relatively low permeability	$1.3 \cdot 10^{-8}$
Side fill with high permeability	$1 \cdot 10^{-5}$
Waste domain with high permeability (except for the waste itself)	$1 \cdot 10^{-5}$
Top fill with high permeability	$1 \cdot 10^{-5}$
Loading areas at tunnel ends with high permeability	$1 \cdot 10^{-5}$
BMA	
Floor fill with high permeability	$1 \cdot 10^{-5}$
Side fill with high permeability	$1 \cdot 10^{-5}$
Concrete enclosure with low permeability that contains the waste	$1.2 \cdot 10^{-8}$
Top fill with high permeability	$1 \cdot 10^{-5}$
Loading areas at tunnel ends with high permeability	$1 \cdot 10^{-5}$
Silo repository	
Sand/bentonite barrier beneath the concrete enclosure with low permeability	$9.3 \cdot 10^{-10}$
Bentonite barrier outside and around (horizontally) the concrete enclosure (this barrier has the lowest permeability of all structures) and the walls of the concrete silo	$3.5 \cdot 10^{-11}$
Concrete enclosure with low permeability that contains the waste (not the outer walls of the concrete silo)	$5.3 \cdot 10^{-9}$
Sand/bentonite barrier above the concrete enclosure with low permeability. There is also a concrete lid on top of the concrete enclosure, which may be fitted with gas evacuation pipes, giving it high permeability	$1 \cdot 10^{-9}$
Top fill on top of the concrete enclosure and sand/bentonite barrier with high permeability	$1 \cdot 10^{-5}$

* Geometric mean value of the components of the anisotropic hydraulic conductivity in different directions /Holmén and Stigsson 2001a/.

The hydraulic conductivity of the structures discussed above is calculated based on the properties of the different materials that occur inside the structures, see /Holmén and Stigsson 2001a/.

A low regional water flow was calculated for the entire period. Simulations with the local model show that the average regional water flow is 3 litres/m^2·year at closure and that it increases to 5 litres/m^2·year after 1,000 years /Holmén and Stigsson 2001a/.

The water flows calculated with the detailed hydrogeological model for the silo repository and the rock vaults plus their waste enclosures are given in Table 6-2 and Figure 6-13. The calculations show that the water flow through all repository parts is low. The water flows through the enclosures in both the silo repository and BMA are very low throughout the period. In the BTF repositories the water flow through the enclosure is higher than for the silo repository and BMA, but compared with the water flow through the entire BTF repositories it is low. The distribution of the water flow through the waste domain in BLA and the water flow through all of BLA is roughly proportional to the difference in the cross-sectional area, since the hydraulic conductivity is the same throughout the repository. The increase in the water flows in the rock vaults with time is due to an increased hydraulic gradient resulting from shoreline displacement.

Table 6-2. Water flows in the silo repository and the rock vaults immediately after closure and water saturation and at 3,000 AD, calculated with the detailed hydrogeological model /Holmén and Stigsson 2001a/.

	Total flow (m^3/year)	
	Immediately after closure and water saturation	3,000 AD
1BTF: Enclosure	2.4	2.7
1BTF: Whole rock vault	7.5	19.4
2BTF: Enclosure	2.4	3.0
2BTF: Whole rock vault	6.7	17.6
BLA: Waste domain	9.6	19.4
BLA: Whole rock vault	13.6	33.1
BMA: Enclosure	0.07	0.13
BMA: Whole rock vault	8.7	36.7
Silo repository: Enclosure	0.23	0.22
Silo repository: Top fill	0.53	1.4

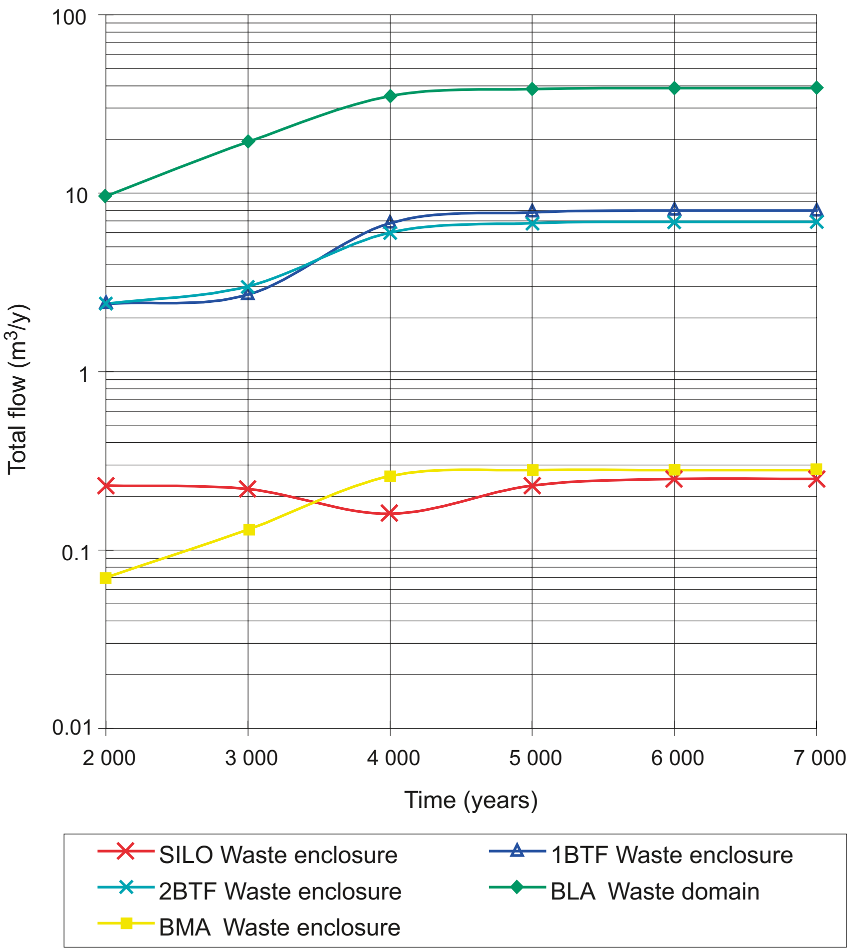


***Figure 6-13.** Water flows through waste enclosures and waste domain in the silo repository and the rock vaults as a function of time calculated with the detailed hydrogeological model /Holmén and Stigsson 2001a/.*

Uncertainty analysis of water flows in the silo repository and the rock vaults

There are two main factors that contribute to the uncertainty in calculated water flows: firstly the uncertainty in the conceptual model, and secondly the generalizations and simplifications that were used when the formal (mathematical) model was set up. A calibration and uncertainty analysis procedure has been used to reduce the uncertainties in the formal model. Calibration and uncertainty analysis do not eliminate the uncertainties entirely, but they do lead to a model for which the uncertainties are limited.

First a calibration was done by inverse modelling of the water flow into the tunnels in SFR 1 /Holmén 2005/. A large parameter variation was used in the inverse modelling, and the realizations that gave good agreement between the calculated water flow and the measured water flow in SFR 1 were accepted. The accepted realizations were then used to calculate future water flows. The parameter uncertainties that have been studied in the calibration of the water flows are:

- the conductivity of the rock mass between the fracture zones,
- the transmissivity of local and regional fracture zones,
- the properties of the hydraulic skin that surrounds the tunnels,
- measured groundwater inflows to the tunnel system,
- heterogeneity of the permeability of the rock mass between the fracture zones,
- a combination of the above parameters.

After the calibration, water inflows through the silo and the rock vaults immediately after closure and water saturation were calculated with the local hydrogeological model, see Figure 6-14. The figure also shows the results of the previous calculations, without uncertainty analysis with the local model. The difference between the median values for the probability distributions /Holmén 2005/ and the previously calculated values /Holmén and Stigsson 2001a/ are mainly due to the fact that the calibration of the open repository in the latter calculations included a hydraulic skin around the tunnels in the model.

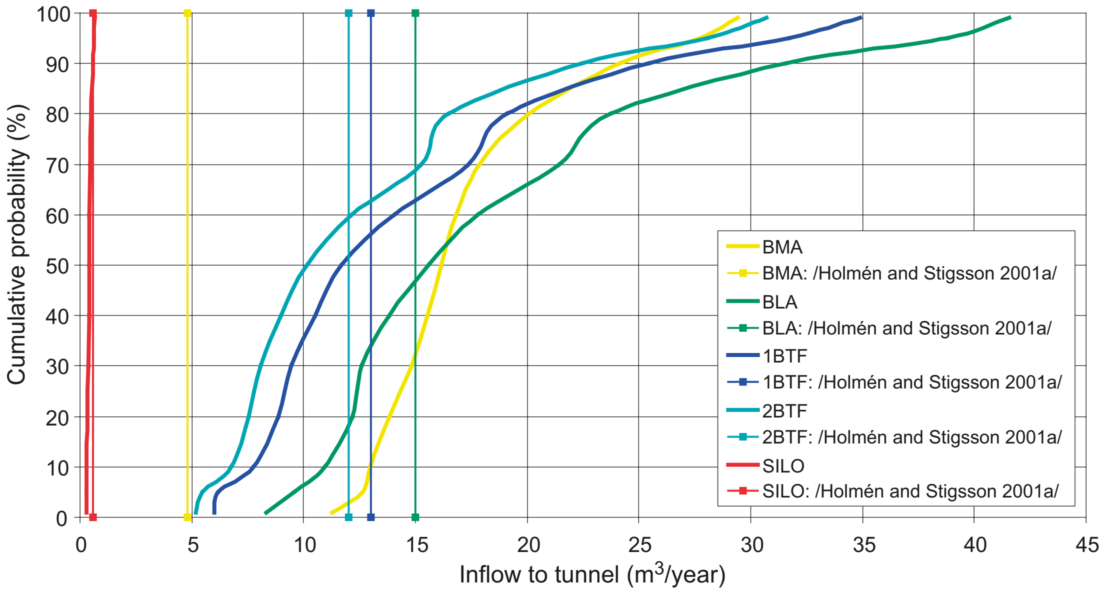


***Figure 6-14.** Probability distribution of water flows through the silo repository and the rock vaults immediately after closure and water saturation /Holmén 2005/. For comparison, water flows calculated previously with the local hydrogeological model hydrogeological model are also shown /Holmén and Stigsson 2001a/.*

The uncertainty analysis that has been performed /Holmén 2005/ is based on the local hydrogeological model in /Holmén and Stigsson 2001a/. The results for the inner parts of the silo and the rock vaults have been calculated without uncertainty analysis with the detailed hydrogeological model /Holmén and Stigsson 2001a/. Probability distributions for the water flow through the silo repository and the rock vaults calculated with the local model have been converted to probability distributions for the detailed water flow through the inner parts of the silo repository and the rock vaults by means of uncertainty factors. The uncertainty factors are calculated as the ratio between the water flow through a rock vault for a given percentile calculated with the local model /Holmén 2005/ and the water flow through the rock vault calculated with the local model /Holmén and Stigsson 2001a/.By multiplying the water flow calculated with the detailed model by the uncertainty factors, probability distributions were obtained for the detailed water flow through the inner parts of the silo repository and the rock vaults.

Water flow between the rock vaults

Water flow between rock vaults entails that waters of different chemical compositions are mixed, for example water flow to BLA can cause the water there to be affected by the concrete environment as well. By analyzing in the hydrogeological model /Holmén and Stigsson 2001a/ which rock vaults occur along a flow path, it is possible to estimate the water flow between the rock vaults. The general conclusion of these analyses is that there is little interaction. The water flow that passes from one rock vault to another is never greater than 10 percent of the water flow from the first rock vault /Holmén and Stigsson 2001a/.The dominant flow paths between the rock vaults and the proportion of water that flows along these paths are given below (based on /Holmén and Stigsson 2001b/).

- Water flow from 1BTF to 2BTF. The flow increases during the period, and at 3,000 AD 10% of the flow passes from 1BTF to 2BTF.
- Water flow from 2BTF to BLA. The flow increases during the period, and at 3,000 AD 5% of the flow passes from 2BTF to BLA.
- Water flow from BMA till BLA. The flow increases during the period, and at 3,000 AD 6% of the flow passes from BMA to BLA.

These results show that the chemical environment in BLA can be affected by the concrete environment in the other rock vaults. The results also show that no flow goes from BLA to the other rock vaults, which means that complexing agents cannot be spread directly from BLA to the other rock vaults. The chemical interaction between the rock vaults is described in section 6.4.4.

Analysis of the flow paths from the repository

The flow paths from the repository are analyzed to be used later for calculation of radionuclide transport through the geosphere. The discharge areas, which are important for the dose calculations, are also determined in the analysis.

Length of flow paths from repository to ground surface

Calculations with the local hydrogeological model show that as long as the sea covers SFR 1, the flow paths from the repository to the ground surface (the sea floor) will be short and mostly vertical /Holmén and Stigsson 2001a/.

A large number of flow paths were generated from the silo and the rock vaults. A statistical analysis of these flow paths is shown in Table 6-3. A visualization of the flow paths immediately after closure and water saturation and at 3,000 AD is shown in Figure 6-15. An uncertainty analysis of the flow paths from the repository, based on parameter values for the accepted realizations in /Holmén 2005/, was performed for two times: immediately after closure water and saturation, and in 5,000 AD /Holmén 2007/, see Figure 6-16. At closure the outflow from the rock vaults takes place mainly along zone 6, which intersects them. After 1,000 years, outflow also takes place along zone 3, which is located directly west of the repository along BMA. The fracture zones around the facility are shown in Figure 4-12.

Table 6-3. Length of flow paths from the silo repository and the rock vaults (results from /Holmén and Stigsson 2001a/).

Time	Median length of flow paths from rock vaults to ground surface [m]				
	BMA	BLA	1BTF	2BTF	Silo
Immediately after closure and water saturation	67	71	77	77	66
3,000 AD (1,000 y after closure)	114	89	125	99	379

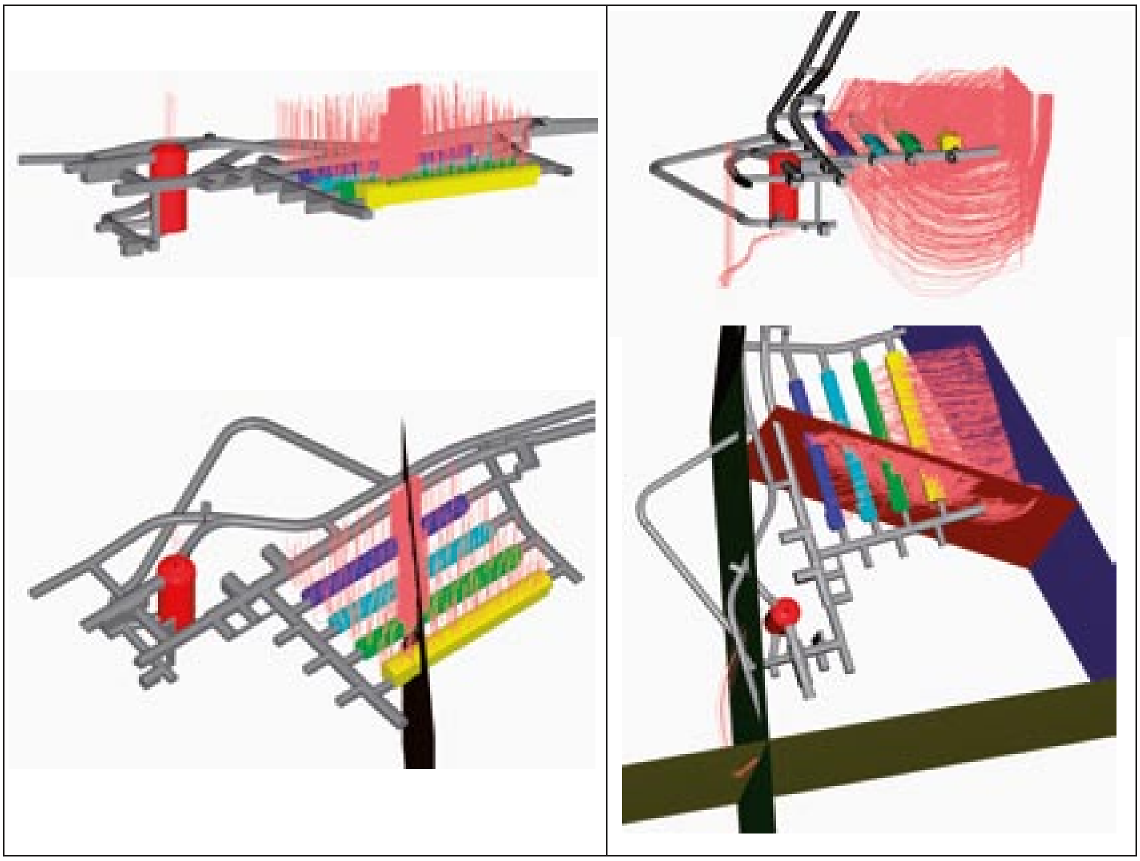


Figure 6-15. *Example of predicted flow paths from the rock vaults at closure (left) and 1,000 years after closure (right). At closure, outflow takes place mainly along zone 6, above the rock vaults and beneath the sea. After 1,000 years, outflow also takes place along zone 3 /Holmén and Stigsson 2001a/.*

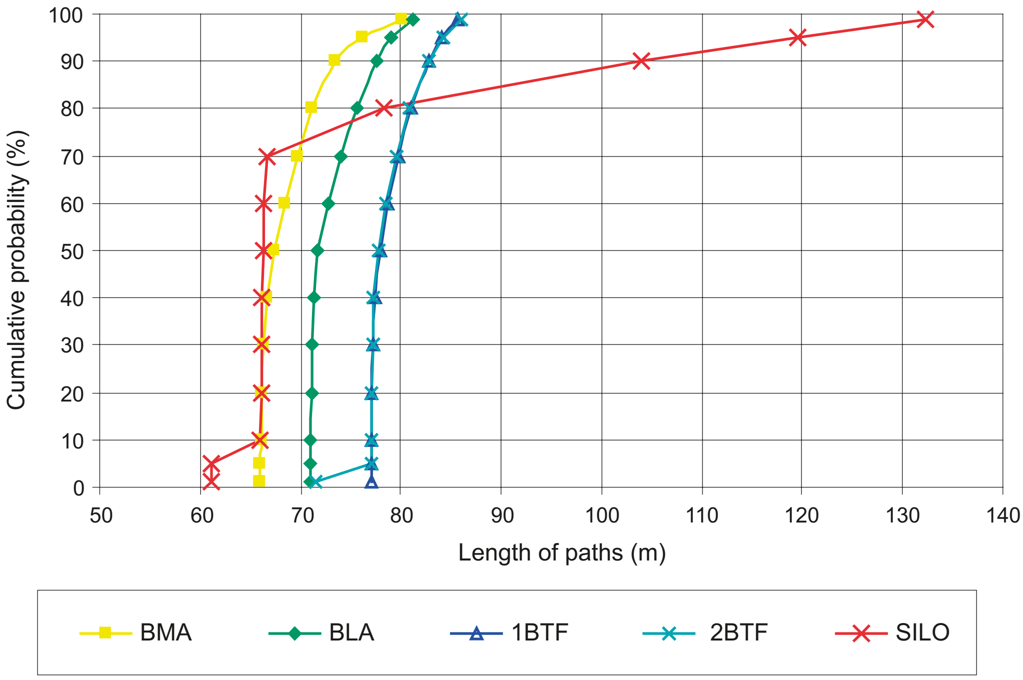


Figure 6-16. *Probability distribution of the length of the flow paths immediately after closure and water saturation (results from /Holmén 2007/).*

Breakthrough times for flow paths from repository to ground surface

Breakthrough times for particles have been predicted with the aid of the local hydrogeological model /Holmén and Stigsson 2001a, Holmén 2007/. The shortest breakthrough times are obtained immediately after repository closure for 1BTF, after about 1,000 years for BMA, BLA and 2BTF, and even later for the silo repository. During the initial period after repository closure the flow paths are short, but the groundwater flow is low. Later during the period the flow paths are still fairly short and the groundwater flow is fairly high. The results of a statistical analysis of the flow paths calculated without uncertainty analysis are reported in Table 6-4 /Holmén and Stigsson 2001a/. Equivalent results for the calculations with uncertainty analysis are reported in Figure 6-17 /Holmén 2007/.

Flow paths in fracture zones from the repository

By analyzing which fracture zones occur along a flow path it is possible to estimate what different fracture zones mean for transport from the repository. The trend is that the importance of the fracture zones increases with time. Initially, zone 6 is the only zone of importance; no flow paths pass any other zones. Later, several zones are of importance as flow paths from the repository, see section 6.5.2.

Table 6-4. Median values of breakthrough times for flow paths from the silo repository and the rock vaults calculated without uncertainty analysis (results from /Holmén and Stigsson 2001a/).

Time	Breakthrough time [years]				
	BMA	BLA	1BTF	2BTF	Silo
Immediately after closure and water saturation	248	56	58	56	313
3,000 AD (1000 y after closure)	52	18	119	44	379

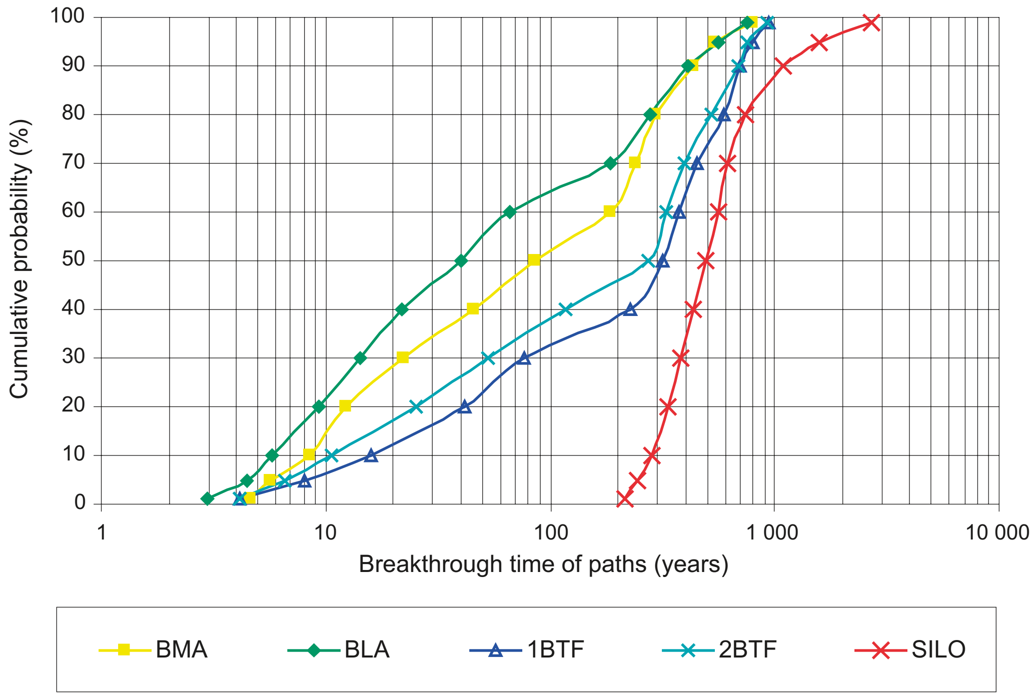


***Figure 6-17.** Probability distribution of breakthrough times for the flow paths immediately after closure and water saturation (results from uncertainty analysis in /Holmén 2007/).*

Discharge areas for flow paths from the repository

The discharge areas for the flow paths from the silo repository and the rock vaults change with time according to the predictions made with the local hydrogeological model. This is due to the fact that the groundwater flow pattern changes when the shoreline is displaced. The most important factors for the situation at the discharge areas is the topography and the position of the shoreline. The model predicts that the most important discharge areas are found along low-lying areas. The largest outflow of groundwater takes place along conductive fracture zones, especially where such fracture zones occur in low-lying areas.

According to the predictions made, the discharge areas for the flow paths from the silo repository and the rock vaults will be situated as follows. At closure, the discharge areas are mainly located directly above the silo repository and the rock vaults (in the sea floor). After 1,000 years, discharge takes place chiefly near the shoreline, which is then quite near SFR 1. The discharge areas for the flow paths from the silo repository are not exactly the same as for the rock vaults. The flow paths from the silo repository and a small portion of the flow paths from 1BTF discharge in an area east of the discharge area for the other rock vaults. The silo repository also has its own discharge area directly above the silo repository. The locations of the discharge areas at two different points in time are shown by Figure 6-18, while Figure 6-19 shows the results of the uncertainty analysis /Holmén 2007/.

Distribution and dilution of discharging groundwater

The analysis of groundwater dilution in the discharge areas shows that under normal conditions, water that has passed through the silo repository or the rock vaults only contributes a percent or so to the total quantity of discharging groundwater in these areas /Holmén and Stigsson 2001a/. It should be pointed out that these results are average values that represent the entire area where the flow paths from the silo repository and the rock vaults discharge. Additional mixing and dilution takes place in the discharge areas by dilution with surface water flows.

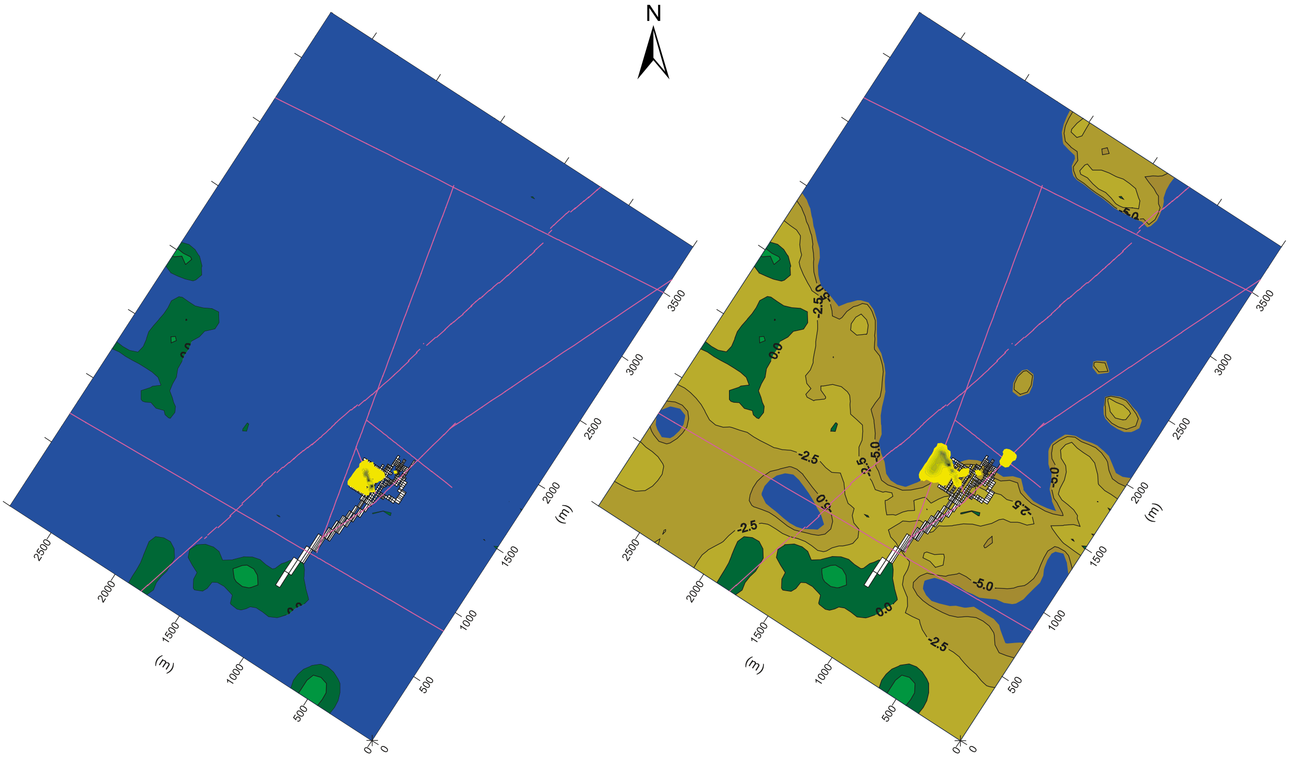


Figure 6-18. *Predicted discharge areas for the water flow from the silo repository and the rock vaults at closure (left) and after 1,000 years (right) calculated with the local hydrogeological model /Holmén and Stigsson 2001a/. The yellow areas mark the location of the discharge areas. The repository with access ramp is marked with small squares and the fracture zones are pink.*

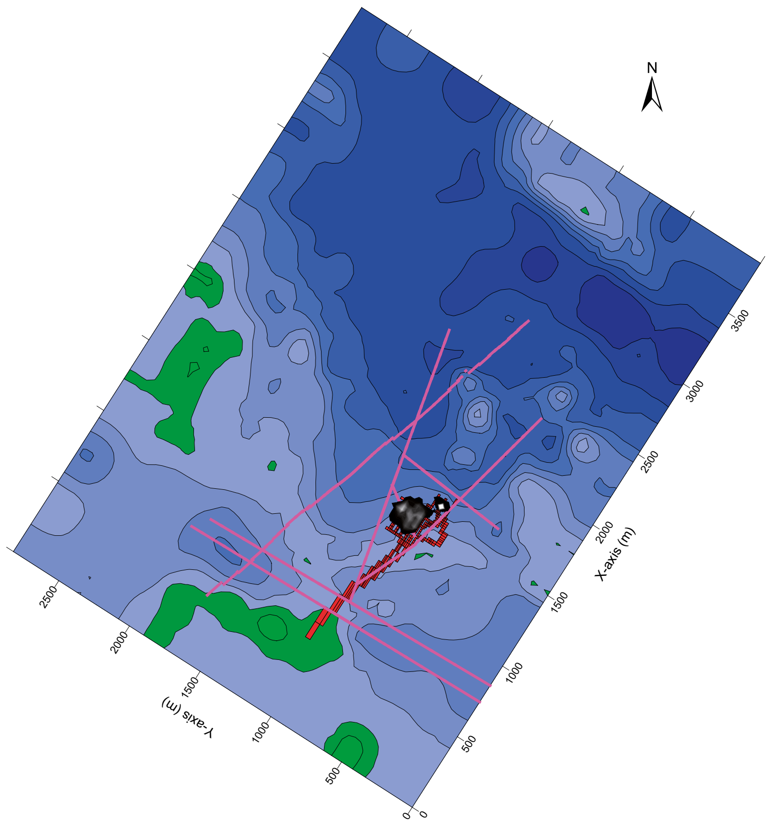


Figure 6-19. *Predicted discharge areas for the water flow from the silo repository and the rock vaults immediately after closure and water saturation. The black-and-white areas represent discharge areas, red shows the repository and the access ramp and pink shows fracture zones (results of the uncertainty analysis in /Holmén 2007/).*

Local wells at SFR 1

At the end of this period, the first 1,000 years after closure, the shoreline will pass above SFR 1. The area will be located so close to the shore that wells are nevertheless not expected until after this period.

Summary

The hydrogeological modelling shows that as long as the sea covers the ground surface above SFR 1, the regional groundwater flow and the water flow in the repository will be small and mainly directed vertically upward. Due to shoreline displacement, however, the sea will recede, and in about 1,000 years the shoreline will be above SFR 1. Due to the receding shoreline, the groundwater flow at SFR 1 will change from a vertical upward to a more horizontal direction

out towards the sea. The size of the groundwater flow will also increase as the shoreline comes closer to the repository. An equivalent increase in the water flow also takes place inside the tunnels, but not inside the enclosure in the silo repository. This is because the silo repository is much less permeable to horizontal water flow than to vertical water flow.

6.4.3 Mechanical evolution

The surrounding rock has good stability. Earthquakes can affect the stability of the rock as well as the stability of the repository. Since it is not possible to predict when future earthquakes will occur and what magnitude they will have, earthquakes are treated as a scenario. Background, statistics and impact of earthquakes are dealt with in the description of this scenario in Chapter 7.

The stability of the rock nearest the rock vaults when rock support elements such as rock bolts and shotcrete no longer have any loadbearing strength is dependent on whether voids in the rock vaults have been backfilled, and if so how. A description of how long a life the rock support elements can be expected to have and what the consequences are when they lose their function is given below.

How the stability of waste, waste packages, and concrete and bentonite barriers evolves depends on a combination of mechanical and chemical processes. The complete description is given in section 6.4.4.

Changes in the rock around the rock vaults cause changes in the size and direction of the water flow, which will also affect radionuclide transport.

The life of rock support elements such as rock bolts and shotcrete is crucial for the long-term stability of SFR 1. As long as these elements retain their loadbearing strength, the changes in stress and deformations in the rock mass around the rock vaults are expected to be small. Rock support elements of the type used in the construction of SFR 1 are normally expected to have a service life of 100–120 years, but it will probably take around 200-250 years for them to completely lose their loadbearing capacity.

When the loadbearing capacity of the rock bolts in particular has declined, rock blocks can be expected to come detached and fall into the rock vaults. This process can continue until a naturally stable arch is formed around the rock vault or over several rock vaults. Backfilling the rock vaults with rigid materials provides support that reduces the loose zone that tends to form around the rock vaults.

In an empty rock cavern this loosening normally proceeds until the cavern has been completely filled with fallen rock so that a support pressure is exerted against the remaining rock. The rock volume that is loosened and falls into the rock cavern increases in volume by about 40 percent. A pessimistic estimate of the greatest extent of the loose zone can be calculated if the size of the volume that must be filled up before a sufficient support pressure has been built up is known. Some loosening is expected to occur in a zone around the rock cavern even in rock caverns backfilled with sand. The size of this zone is estimated to be about two metres. It is difficult to estimate how long the loosening process will proceed before stable conditions are obtained. Based on experience from cave-ins in abandoned mines, this is estimated to take 50–150 years.

In the case of SFR 1, the rock vaults are expected to remain stable for 200–250 years with the existing rock support. After this a loosening of the rock around the rock vaults occurs that is expected to last 50–150 years until stable conditions are obtained. A pessimistic estimate of the maximum size of the loose zones is shown in Figure 6-20. Provided the BMA and BTF repositories are backfilled with sand, the extent of the zone is estimated to be two metres, while the loose zone around BLA is estimated to be five metres if the rock vault is not backfilled /Fredriksson 2000/. The size and shape of the loose zone can vary by about 50 percent depending on the variation in rock quality and the direction of the fractures in relation to the rock vaults.

The analysis by /Fredriksson 2000/ shows that BMA should be top-filled so that a connection is not formed between BMA and BLA. Furthermore, in conjunction with the closure of BLA, measures should be considered to reduce the void volume and thereby limit the size of the loose zone. Closure is arranged in such a manner that a direct connection is not created between BLA and BMA.

Figure 6-20. *The figure shows that in rock vaults that are backfilled with sand (BMA and BTF), the depth of the loose zone (shaded) is generally expected to be about two metres. The size of the loose zone around BLA has been estimated to be five metres if BLA is not backfilled /Fredriksson 2000/.*

6.4.4 Chemical evolution

Together with the mechanical evolution of the repository, the chemical evolution is of importance for judging the durability of the engineered barriers in the repository, for the release of radionuclides and other species, and in particular for sorption.

The durability of the engineered barriers is affected by chemical reactions that take place when the barriers come into contact with the groundwater. Three studies have been carried out of the geochemical reactions in SFR 1 /Höglund 2001, Gaucher et al. 2005, Cronstrand 2007/. Gas formation can give rise to cracking. Leaching and formation of different phases can cause porosity changes and cracking, which in turn affects radionuclide transport via advection and diffusion through the barriers. A change in the composition of the barriers also affects sorption.

Good sorption of radionuclides in concrete is one of the defined safety functions for SFR 1, see Chapter 5. A prerequisite for good sorption is a favourable chemical environment. Sorption of different radionuclides is affected in different ways by the chemical environment. The chemical environment in the cement pores, high pH and high calcium concentration, mean that the carbonate concentration is low, since it is regulated by the calcite equilibrium. Carbonate is otherwise a strong complexing agent and could prevent the sorption of numerous radionuclides. In the same way, high pH values and high calcium concentration keep the concentration of numerous other ligands low, such as oxalate. Several of the radionuclides are redox-sensitive, with lower sorption under oxidizing conditions. High ionic strength means lower sorption for certain radionuclides. Complexation, where organic compounds form soluble complexes with radionuclides, can reduce sorption.

There are large quantities of organic compounds in SFR 1, mainly in the waste. Organic material, above all cellulose, is a possible source of energy and nutrients for microorganisms. Microorganisms can degrade the organic material to various components, which can create problems depending on how extensive the degradation is. The microbial activity is dependent on the passage of a water flow through the repository, among other things for the transport of nutrients to microorganisms but also for the removal of the waste products of metabolism, which can otherwise poison the microorganisms. Since the water flow through the repository is low, microbial activity is also low. For this reason, the microbial impact on SFR 1 is expected to be little /Pedersen 2001/. Furthermore, the environment in SFR 1 is special and in no way optimal for microbial life. The nearest we can come to an analogue is probably refuse tips and various types of landfills. These contain microbial activity with degradation of the waste, resulting in the formation of waste products. Lessons learned from studying such analogues and from experiments conducted under repository-like conditions can show what will happen in SFR 1. A review of microbial processes that may occur in SFR 1 is presented in /Pedersen 2001/.

Composition of the groundwater

The chemical composition of the groundwater is of importance for how the system will evolve. The groundwater that enters the repository will be affected by the materials in the repository via various processes. The composition of the water will also be affected by the water flow through the repository, where waters of different compositions are mixed.

SFR 1 is covered today by the Baltic Sea, and the groundwater flowing into the repository can be characterized as a saline groundwater. Due to the ongoing process of shoreline displacement, the boundary conditions for the groundwater flow will change over time.

The shoreline will pass over SFR 1 approximately 1,000 years after closure. As a result, the flow pattern of the groundwater will be changed and the origin and chemical composition of the water that reaches the silo repository and the rock vaults will change. According to the hydrogeological model /Holmén and Stigsson 2001a/, the water will change during the period up to 2750 AD from an old groundwater (with a high chloride content) to a young groundwater (with a lower chloride content). The big change in type of groundwater will take place between

2300 and 2750. The young groundwater originates from recharge areas near the repository. The conclusion is thus that inflow of saline groundwater will dominate during the first 1,000 years.

The reference composition of the penetrating saline groundwater after saturation of the repository is given in Table 6-5 /Höglund 2001/. The basis for the reference composition of the groundwater is measurements made during the construction of SFR 1 (1984–1986), data from the monitoring programme for SFR 1 (1989–1999) and geochemical calculations /Höglund 2001/.The monitoring programme and how the composition of the penetrating groundwater has changed are described in section 4.9.4. The results of the most recent measurement in 2006 of the water from boreholes included in the monitoring programme are shown in Table 4-6. In the geochemical calculations, the water composition was adjusted so that the water is in thermodynamic equilibrium with commonly occurring minerals in the rock. The content of calcium and magnesium was adjusted so that the water is in equilibrium with calcite and dolomite, and a silicate content (equilibrium with quartz) was added so that the results would be more accurate when the degradation of concrete was calculated /Höglund 2001/.

Evolution of the barriers

The different repository parts in SFR 1 have different barriers. In the silo repository all waste is conditioned, nearly half of the waste packages are of concrete, all waste packages are embedded in porous concrete, there is an inner compartment structure of concrete, the outer walls are made of thick concrete, and the concrete silo is surrounded by bentonite. BMA has a simpler concrete structure, more than half of the waste packages are of concrete, and all waste is conditioned. In 1BTF and 2BTF, the barriers consist of the concrete tanks and the grouting concrete surrounding the concrete tanks and the steel drums. In BLA there are no barriers with any long-term function. A more detailed description of the different repository parts and their barriers is provided in General Part 1, “Facility design and operation”, Chapter 5, “Description of facility and function”.

The permeability of waste packages and other barriers to water and gas is of importance for the release of radionuclides from the different repository parts. This permeability is mainly dependent on geometries, material properties and porosity, as well as the occurrence of cracks in the materials. These properties and the composition of the materials also affect the diffusion and sorption of the radionuclides in the materials. The processes that can cause changes in these properties are discussed in this section.

Table 6-5. Composition of penetrating saline groundwater based on measurement data from SFR 1 and geochemical calculations (ion concentrations in [mg/l] /Höglund 2001/.

Parameter	Reference value	Min. value	Max. value
Redox [mV]	Reducing	–100	–400
pH	7.3	6.5	7.8
SO_4^{2-}	500	20	600
Cl^-	5,000	3,000	6,000
Na^+	2,500	1,000	2,600
K^+	20	6	30
Ca^{2+}	430	200	1,600
Mg^{2+}	270	100	300
HCO_3^- (alk)	100	40	110
Si as SiO_2(aq)	5.66	–	–
Electrical balance, %	–0.04%		

Concrete and bentonite barriers

With time the properties of the concrete and bentonite barriers change due to a number of chemical processes. Interaction between concrete and groundwater leads firstly to leaching of highly soluble alkali hydroxides. This is followed by a leaching of calcium hydroxide (portlandite), which is an important constituent in the cement paste in the concrete. When the portlandite has been leached out, an incongruent dissolution of calcium silicate hydrate (CSH) phases begins. The leaching process leads to a gradual lowering of the pH in the pore water in the concrete. In summary, the calcium silicate hydrate phases degrade according to the following scheme:

CSH_1.8 → CSH_1.1→ CSH_0.8 (tobermorite).

CSH stands for calcium silicate hydrate, and the number after CSH stands for the ratio of Ca to Si. In other words, the calcium/silicate ratio decreases due to leaching.

There is great uncertainty regarding how bentonite reacts at high pH. The study by /Gaucher et al. 2005/ takes into account results obtained in the EU-funded project ECOCLAY-II, which studied interactions between cement and clays /Gaucher et al. 2004, EUR 2005/. According to /Gaucher et al. 2005/, the dissolution of montmorillonite, the main constituent of bentonite, in alkaline media produces Al, Si, Mg and Na. These elements can be precipitated in the form of various silicates and aluminosilicates.

If the alkaline fluid is rich in potassium, illite can be formed. Illite is a clay mineral without the capacity to shrink or swell. If the pH increases even more close to the concrete, illitization may be followed by precipitation of phillipsite-K (an aluminosilicate).

The reactions that will take place in the bentonite when the pH increases if the environment has a low potassium content are summarized below /Gaucher et al. 2005/ along with supplementary information on the minerals:

Montmorillonite	clay mineral of the smectite type that has shrinking and swelling properties and a high ion exchange capacity
↓	
Beidellite	clay mineral of the smectite type
↓	
Saponite	clay mineral of the smectite type
and	
Clinochlore	rock mineral. Clinochlore is the most common chlorite.
↓	
Zeolites	rock minerals, hydrated aluminosilicates such as analcime, chabazite, mordenite and phillipsite-NaK.
↓	
Gismondine	rock mineral of the zeolite type
and	
Gyrolite	rock mineral, a silicate without aluminium

Three studies have been carried out for SFR 1 of the chemical interaction between concrete barriers and groundwater, and in the two latter studies bentonite as well. The purpose has been to estimate both the timescale and the magnitude of potential changes in the chemical composition of the barriers and consequential changes in the transport properties of the barriers /Höglund 2001, Gaucher et al. 2005, Cronstrand 2007/. The main purpose of the latter study /Cronstrand 2007/ is to see the impact of climate change, especially permafrost, farther in the future. The calculations have been carried out with coupled chemistry and transport models (PHREEQC-2 in /Höglund 2001/, PHAST in /Gaucher et al. 2005/ and PHREEQC-2.13 in /Cronstrand 2007/). This enables an assessment to be made of the combined effect of the processes that take place simultaneously in the system. Porosity changes are not included in the version of PHAST that was used in the modellings /Gaucher et al. 2005/.

The impact of the saline groundwater (Table 6-5) on degradation of concrete has been modelled for a 1 m thick concrete slab for a period of 10,000 years /Höglund 2001/. The changes in the silo repository with a system of rock, bentonite, concrete and the interior of the silo have been modelled up to 100,000 years /Gaucher et al. 2005, Cronstrand 2007/. The groundwater composition in the study by /Gaucher et al. 2005/ is slightly different than in the other two studies, but within the stipulated minimum and maximum values (see Table 6-5). The calculations were done for the type of structural concrete used in bottoms, walls and lids in the silo repository and in the structures in BMA.

The porosity of a completely hydrated structural concrete of the type used in SFR 1 is about 10% /Höglund 2001/. In the event the exchange of dissolved components between the groundwater and the concrete is controlled by diffusion in the concrete's pore system, the biggest changes in mineral composition and porosity take place during the first 1,000 years in a zone near the interface between the concrete and the groundwater flowing past. The porosity in the decimetre of concrete closest to the interface between groundwater and concrete declines from 10% to at most approximately 8% (6% at the interface), after which it increases with time so that it is slightly higher than 10% at 1,000 years /Höglund 2001/. Deeper in the concrete the porosity varies less and much more slowly. At a distance greater than 4 dm from the interface with the flowing groundwater, the reduction in porosity is negligible during the first 1,000 years /Höglund 2001/. The system without bentonite, corresponding to BMA, was also studied by /Cronstrand 2007/. It was found that the porosity changed much more slowly. During the first thousand years the porosity did not change at all. If the concrete is not in direct contact with flowing groundwater but is surrounded by a bentonite barrier, the bentonite barrier contributes to slowing down the leaching process. During the period in question, i.e. the first thousand years, no impact on the porosity of either the concrete or the bentonite is seen in the calculations for the silo repository /Cronstrand 2007/.

The initial mineralogical composition of the multi-barrier system "waste matrix – grout – silo wall – bentonite – shotcrete – rock" that was studied by /Gaucher et al. 2005/ is shown at the top in Figure 6-21. The calculated changes in the concrete structure and the rock after 500 years are, as expected, very small and the waste matrix is completely unaffected, see at bottom in Figure 6-21.Some changes have taken place in the bentonite, however. At the boundary between the bentonite and the silo wall/shotcrete, the sodium montmorillonite in the bentonite has weathered and some new minerals have been formed, above all the zeolite chabazite. These newly formed phases have a high molar volume, which means that the precipitate will block the pores or at least sharply reduce the porosity of the bentonite barrier near the silo wall /Gaucher et al. 2005/. The transformation to zeolites also gradually reduces the swelling capacity of the bentonite barrier.

In the concrete in the silo wall, some degradation of portlandite in particular has occurred and a new mineral phase, CSH_1.1, has formed. Of the original phases, additional ettringite has precipitated.

The conclusions from the geochemical modellings of the changes in the concrete and bentonite barriers during the period in question, the first 1,000 years after closure, are that:

- The porosity of the bentonite is insignificantly affected.
- The porosity of the bentonite nearest the concrete surfaces decreases slightly.
- Portlandite still remains in the concrete. Portlandite reacts rapidly and a high pH (greater than 12) is maintained as long as portlandite remains.
- The various modellings do not provide a definitive answer to the question of how the bentonite will be altered, but some degradation of the main constituent of the bentonite, sodium montmorillonite, is expected nearest the concrete surfaces.
- These changes are small and are not expected to affect either conductivity, diffusivity or sorption capacity in the concrete and bentonite barriers.

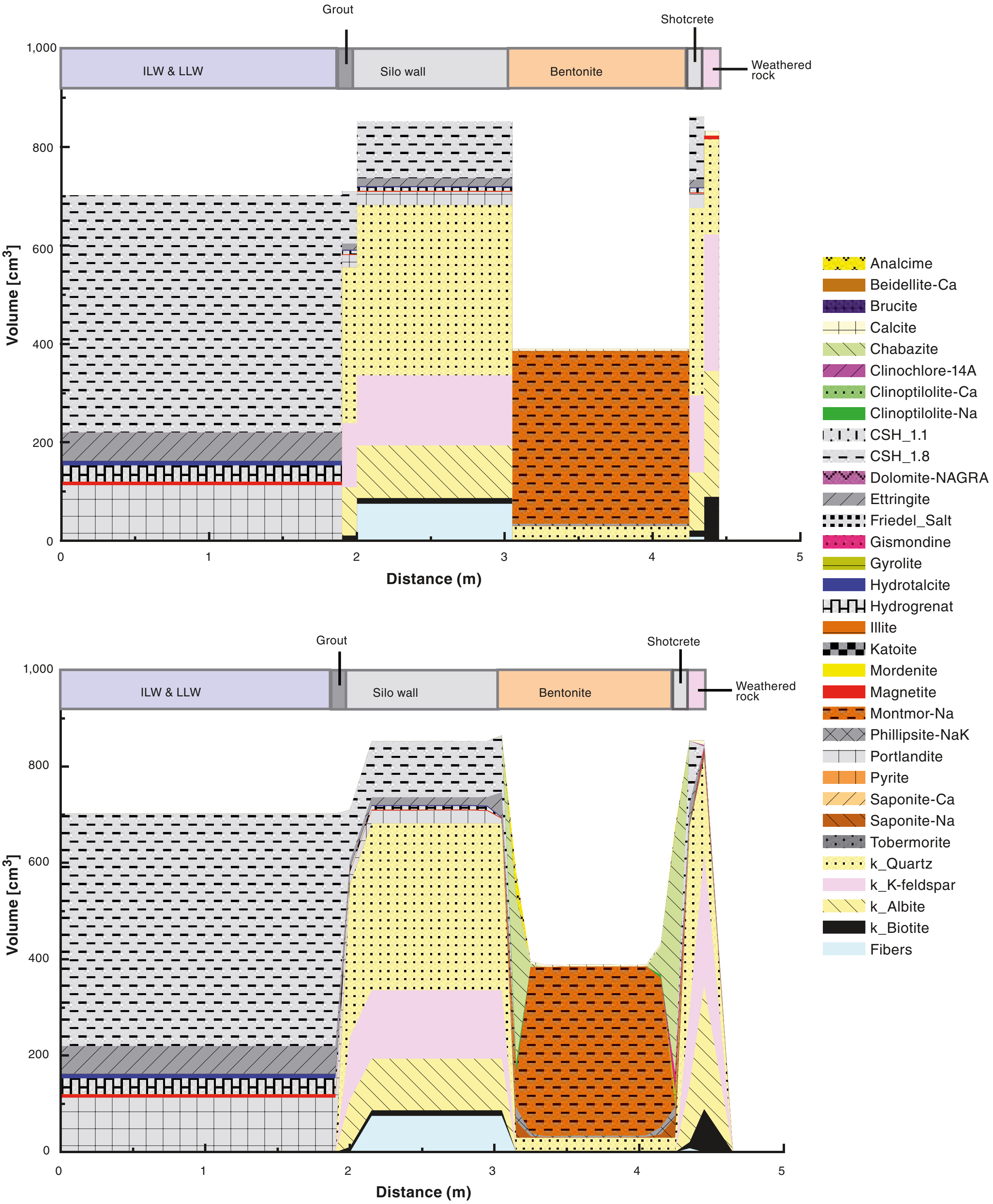


Figure 6-21. *Mineralogical composition in the system waste matrix – grout – silo wall – bentonite – shotcrete – rock at closure and after 500 years of leaching (simulation with normal pore diffusion, weathered rock and saline groundwater) /Gaucher et al. 2005/.*

Other chemical and mechanical processes in concrete barriers

Previous analyses of the conditions in SFR 1 have shown that the amount of sulphate that is obtained on complete degradation of all ion exchange resins in the silo repository and the volume increase that results when the sulphate reacts with cement and concrete can be taken up by the available expansion volume /Höglund 1989/. Sulphate is not expected to be leached from the package since the conditioning cement is able to bind all sulphate, provided the waste does not contain an extremely proportion of ion exchange resins. It is therefore not likely that any cracks will form in the grouting concrete or concrete structures due to the fact that sulphate from ion exchange resins forms ettringite inside or outside the waste packages. Furthermore, experimental data indicate that ion exchange resins should be stable at the low temperatures and radiation doses that will exist in SFR 1 /Savage et al. 2000/.

Carbonatization due to reactions with carbon dioxide formed by decomposition of organic material in waste can clog pores in the concrete and in extreme cases also cause cracking. This primarily affects cement and concrete in the waste packages if the waste is solidified with cement and/or packed in concrete moulds. Furthermore, the quantity of degradable organic material in the silo repository is relatively small and the conditions in other respects are not particularly favourable for sustaining microbial activity in either the silo repository or the rock vaults that have concrete barriers /Pedersen 2001/. This suggests that only limited quantities of carbon dioxide will be formed. The process as such has not been analyzed in greater detail, but it is unlikely that it would lead to cracking.

Dissolution of salt in evaporator concentrate conditioned in bitumen can release chlorides, carbonates and sulphates, which can in turn react with surrounding concrete barriers. Ions can also be released from the ion exchange resins. Water uptake in the bitumen matrix is slow, which means that the dissolution of dissolved salts takes place during a relatively long period of time (see section below headed “Waste packages and waste matrices”).This suggests that the impact on surrounding concrete should be small. However, without a more detailed analysis the possibility cannot be ruled out that with the passage of time (above all after the first 1,000 years), such high concentrations of these dissolved salts could form locally that nearby concrete could be affected, leading to porosity changes and possibly also cracking.

The reaction products that are formed when reinforcing bar in the concrete structures corrodes can lead to cracking of the concrete around the rebar. This is a well-known phenomenon that is taken into consideration in determining the thickness of the concrete layer over the rebar. This mechanism is not expected to lead to penetrating cracks in the concrete structures either.

There are a number of other processes that could mechanically affect the concrete barriers and at worst cause them to crack. Volume increase of waste matrices and waste packages due to water uptake in ion exchange resins conditioned in bitumen and formation of expansive corrosion products can induce stresses in surrounding concrete barriers unless sufficient voids are available to take up this volume increase. Build-up of internal gas pressures and settlements and movements in the different barriers or other mechanisms that could eventually cause cracks in the concrete barriers. The consequences of these types of mechanical effects have not been analyzed in detail, and the possibility cannot be completely ruled out that they could eventually cause minor cracking of the concrete barriers due, for example, to settlements or pressure build-up.

Some microorganisms can, especially in the absence of oxygen, form acids which can in principle affect the cement and concrete structures in SFR 1. But except during a short initial period, conditions in SFR 1 will be oxygen-free, so acid formation will be negligible.

The hydraulic conductivity of the concrete barriers in the silo repository and BMA has been chosen so that it applies to concrete with a few minor penetrating cracks /SKB 2001c/. Cracking is not expected to be so extensive during the first 1,000 years as to affect conductivity.

Waste packages and waste matrices

The waste in SFR 1 is packed in containers of steel or concrete, and in many cases the waste inside the container is embedded in cement or bitumen.

Steel containers

Due to corrosion, steel containers have not been regarded in the assessment as a barrier to the transport of water, gas or radionuclides. The corrosion products that are formed during the operating phase – iron oxides and possibly iron hydroxides – can be good sorbents for radionuclides that occur in the water as cations. Metal ions that have properties similar to iron could also be co-precipitated with the corrosion products. In the assessment, products from corrosion of iron and steel have not been regarded as a sorption barrier, even though there are strong indications that iron oxides and iron hydroxides can sorb and co-precipitate many elements. On the other hand, corrosion of iron and steel gives rise to reducing conditions in the repository, which is taken into account in the assessment.

Sulphate-reducing bacteria have the ability to form sulphide, which can have a corrosive effect on metals. Under special conditions, with local water flows near metal surfaces and in the presence of organic compounds from the repository, some pitting can occur. Pitting is not of primary importance for SFR 1 since no special requirements are made on the integrity of the metal containers over long periods of time, and pitting does not cause more gas production than general corrosion.

Concrete containers and cement matrices

Calculations regarding leaching of concrete show that concrete containers and cement matrices will not be subjected to any significant leaching of cement components during the time period /Höglund 2001, Gaucher et al. 2005, Cronstrand 2007/.

After a long time, the penetration of chloride from groundwater could possibly cause small mineral transformations in the concrete, but without appreciably affecting the properties of the moulds. Corrosion of reinforcing bar and the resultant volume increase could cause small cracks in the concrete nearest the rebar. This is not expected to be of importance for the properties of the concrete moulds as barriers for radionuclides either. But the possibility cannot be ruled out that some cracking of cement matrices will occur as a result of corrosion of metals in the waste and the volume increase caused there by the corrosion products.

Other processes that could with time, though scarcely during the first 1,000 years, cause cracking of concrete containers and cement matrices are carbonatization and ettringite formation in the pores when sulphate from degraded ion exchange resins reacts with cement minerals. A complete degradation of ion exchange resins can lead to such extensive ettringite formation that the concrete moulds burst. However, the conditions in SFR 1 do not favour a complete degradation of the ion exchange resins. Furthermore, the conditions in the waste packages are not particularly favourable for microbial activity with formation of carbon dioxide which can lead to carbonatization of concrete and cement in waste packages, accompanied by clogging of pores and possible cracking /Pedersen 2001/.

Build-up of an internal gas pressure is another mechanism which could theoretically cause cracking of cement matrices and concrete containers.

Concrete containers and cement matrices in the silo repository, BMA and BTF are not expected to undergo changes in properties due to leaching of the cement minerals. This suggests that these barriers will retain their diffusion and sorption properties throughout the time period, the first 1,000 years. The hydraulic conductivity of the concrete barriers in BMA and BTF has been chosen so that it applies to concrete with a few minor penetrating cracks /SKB 2001c/. Cracking is not expected to be so extensive during the first 1,000 years as to affect hydraulic conductivity.

Waste matrices of bitumen

The bitumenized waste in SFR 1 consists primarily of ion exchange resins, but also some evaporator concentrate. Bitumen is in itself an effective barrier to both water and solutes. However, in a waste package where bitumen is mixed with ion exchange resins and evaporator concentrate, the properties of the bitumen matrix can change with time. Processes that can lead to such changes are radiolysis, biodegradation, ageing and water uptake.

Radiolysis of bitumen due to irradiation from the radionuclides in the waste can form gas bubbles in the matrix, which in extreme cases can mean that pores and cracks form in the matrix. Due to the low radiation levels, radiolysis is not expected to affect the bitumen matrix except in the most radioactive waste packages, where some swelling of the matrix might occur /Pettersson and Elert 2001/.

Biodegradation of bitumen in SFR 1 is not expected to affect the properties of the bitumen matrix. The reason for this is that this type of degradation is generally a very slow process /Pettersson and Elert 2001/ and that the environment in SFR 1 is unfavourable for microbial activity /Pedersen 2001/.

Ageing of bitumen in air entails that the material becomes harder and more brittle, but it is doubtful whether this occurs in an oxygen-free environment under water in a closed SFR 1. Embrittlement probably does not occur after closure, but if it did the consequence would be that cracks are more likely to form if the matrix swells, for example due to gas generation and water uptake.

Water uptake in a bitumen matrix takes place by diffusion into ion exchange resins and salt in evaporator concentrate, which is hygroscopic. When the waste, especially ion exchange resins, takes up water it increases in volume and the entire bitumen matrix swells. The consequences of this could be to open up an interconnected porosity in the bitumen matrix and cracking of the matrix due to the stresses caused by the swelling. How rapidly water is absorbed depends largely on the proportion of ion exchange resins in the matrix. The proportion of ion exchange resins in bitumen in SFR 1 suggests slow water uptake. However, in the case of a few waste types with a higher proportion of ion exchange resins, water uptake could proceed relatively rapidly /Pettersson and Elert 2001/.

The swelling of the bitumen matrix that takes place in connection with water uptake can also affect surrounding barriers if insufficient expansion volume is available. A calculation of the theoretically maximum swelling indicates that the volume increase could be greater than the void inside the waste package in the case of certain waste types in the silo repository and BMA /Pettersson and Elert 2001/. In BMA, however, there are additional voids outside the waste packages if the packages are not grouted. However, the waste type in the silo repository for which the maximum volume increase could theoretically exceed the void in the waste package and the extra void that exists in the form of an expansion box deposited together with the drums has such a low proportion of ion exchange resins that the rate of water uptake and thereby volume increase should be very slow.

The main degradation of bitumen matrices that leads to release of radionuclides in the waste is expected to be water uptake and swelling. The time for water uptake and how this affects the matrix is very uncertain, however. Some indication of how effective a bitumen matrix is as a barrier for radionuclides can be obtained from leaching experiments. Extrapolation of results from such leaching experiments conducted over periods that are short in these contexts indicates that it could take several thousand years before all radionuclides have leached out of the bitumen matrix in a 200-litre steel drum /Pettersson and Elert 2001/. Despite this it is probable that long-term changes in the properties of bitumen due to water uptake in combination with ageing speed up the release of radionuclides from the bitumen matrix. In view of this, a more reasonable timescale for the release of radionuclides is, according to /Pettersson and Elert 2001/, several hundred up to a thousand years.

Gravel/sand backfill

Backfilling with gravel or sand is planned in the silo repository, BMA and BTF, see section 4.2. Alkali hydroxides and portlandite leached from the concrete in these repository parts can react chemically with the gravel or sand backfill outside the concrete barriers. Primary silicate minerals such as quartz and feldspar are dissolved and secondary calcium silicate hydrate (CSH) phases are precipitated at the same time as hydroxide ions are consumed /Savage 1997, Holgersson et al. 1998/. These phases alter the properties of the surfaces, such as the specific surface area. Experiments have shown an increase from around 0.3 m^2/g to around 1.1 m^2/g for a rock specimen that has reacted with cement water /Holgersson et al. 1998/. Changes in the properties of the surface can affect the sorption of radionuclides. Sorption of CSH phases on metal ions is often higher than on rock minerals /Savage 1997/. The possible improvements in sorption capacity cannot be disregarded in the assessment.

The transformation to secondary CSH phases may entail some volume increase of the solid phase and thereby a reduction in the porosity of the gravel backfill. This has been shown in column experiments where cement water flowed through finely crushed material /Bateman et al. 1995/. The volume increase resulting from the formation of secondary CSH phases and possible precipitation of calcite and brucite can lead to reduced porosity. The possible reduction in porosity is disregarded in the choice of diffusion coefficient in the gravel backfill, and the possible impact this may have on the hydraulic conductivity in the backfill is allowed for in the relatively low value that has been assumed for unaffected gravel in the assessment (10^{-5} m/s, /Holmén and Stigsson 2001a/).

Water composition in the barriers

Based on the composition of the barrier material and inflowing groundwater, the expected evolution of the hydrochemical conditions in the barriers in the different repository parts can be assessed.

pH

The groundwater that enters the repository after closure has a neutral pH. In the silo repository, BMA, 1BTF and 2BTF, the water will be affected by the concrete, while the small quantities of concrete in BLA will have little effect on the pH and then only locally.

The concrete mainly affects the pH in the inflowing groundwater. The pore water in fresh concrete has a pH that is higher than 13 owing to leaching of highly soluble alkali hydroxides. When they have been leached out, the pH is buffered to about 12.5 by calcium hydroxide (portlandite). If the portlandite is also leached out, a dissolution of calcium silicate hydrate (CSH) phases begins. During this dissolution phase, the ratio of calcium to silicate in the concrete changes and the pH is gradually reduced to about 11. Continued dissolution of the remaining cement gel leads to a reduction in the pH of the pore water to about 10.

The concrete structures in SFR 1 are made primarily of Degerhamn Anläggningscement. An analysis of cement pore water from fresh and leached cement is presented in Table 6-6. The analyses show that the highly soluble alkali hydroxides cause a high pH, which is lowered when they are leached out.

The calculations in /Höglund 2001/ show that the pH is expected to be buffered by the leaching of portlandite, i.e. to be above 12, in most of the concrete barriers during the first 1,000 years. This is confirmed by the two later studies /Gaucher et al. 2005, Cronstrand 2007/.

The leaching of alkali hydroxides and portlandite from the concrete can raise the pH in the backfill of sand or gravel in BMA, 1BTF and 2BTF and possibly also affect the gravel fill at the top of the silo repository. Depending on time and distance from the concrete, the pH in these materials can vary between the pH in inflowing groundwater and the pH in concrete water.

Table 6-6. Analysis of cement pore water from fresh and leached cement (ion concentrations in [mmol/l].

Parameter	Fresh cement[a)]	Leached cement[b)]
pH	13.1	12.6
SO_4^{2-}	0.04	0.02
Cl^-	<0.06	2 [c)]
Na^+	28	3 [c)]
K^+	83	0.1 [c)]
Ca^{2+}	0.9	20
Si_{tot}	0.8	0.003
Al_{tot}	0.04	0.002
OH^-	114	36

[a)] Expelled pore water /Lagerblad and Trägårdh 1994/.

[b)] Crushed cement, analysis of leachate /Engkvist et al. 1996/.

[c)] Same concentration as in original leachate.

Alkali hydroxides and portlandite leached from the concrete can react chemically with minerals in the backfill. Primary silicate minerals such as quartz and feldspar are dissolved and secondary calcium silicate hydrate is precipitated at the same time as hydroxide ions are consumed /Savage 1997, Holgersson et al. 1998/. Mass balance calculations done for the deep repository for other long-lived waste /Karlsson et al. 1999/ show that the backfill of sand or gravel has sufficient capacity to neutralize hydroxide ions leached from the concrete structure. SFR 1, especially BMA and BTF, and the planned repository for other long-lived waste are so similar in terms of quantities of concrete and backfill of sand or gravel that the conclusion from the calculations can be considered to be applicable to SFR 1 as well. Complete neutralization in the gravel fill means that the pH in the surrounding rock does not exceed the pH in the groundwater. The study for other long-lived waste has been criticized in a study of the buffering capacity of the backfill on pH carried out for SKI /Benbow et al. 2002/. Calcium silicate hydrate, which was chosen as an end product in the reaction used in the mass balance calculations, was not considered to be a conservative choice. Even with the less conservatively chosen end product, the mass balance indicates complete neutralization. The quantity of silicate material, and above all the available reaction surface area, are judged to be overestimated in the study for other long-lived waste /Benbow et al. 2002/. This leads to the conclusion that a fine-grained material should be used as backfill if the spread of high pH from the repository to the surrounding rock needs to be limited.

Leaching of concrete can also cause changes in pH in the bentonite and sand/bentonite barriers. The uncertainties in how bentonite reacts at high pH are great, and the future evolution of pH in these barriers is therefore difficult to predict. A high pH is above all judged to be of importance for the chemical transformation of the chemical barriers. If the hydroxide ions do not react with the materials in these barriers, the pH will become high relatively quickly /Höglund 2001/. According to the two later studies of the degradation of the silo repository, only a small increase of the pH in the bentonite immediately adjacent to the concrete is obtained during the first thousand years /Gaucher et al. 2005, Cronstrand 2007/.

Redox conditions

The oxygen that is present in the repository at closure will be dissolved in the inflowing groundwater. This oxygen will quickly be consumed by corrosion of steel in, for example, containers and reinforcing bar, oxidation of dissolved iron(II) and sulphide in the water, and microbial processes. A low redox potential will be maintained in the different repository parts due to the release of Fe^{2+}ions in connection with anaerobic corrosion of steel and from corrosion products.

Ionic strength

Ionic strength affects sorption, especially for nuclides that sorb via ion exchange. This applies above all to alkali metals and alkaline rare-earth metals. The counterions to chloride, calcium, sodium and potassium compete with the nuclides, resulting in reduced sorption at high chloride concentration. The concrete environment entails an initially high ionic strength in all repository parts. Due to the relatively saline groundwater in the rock during the first 1,000 years, the ionic strength is expected to be high in the surrounding rock as well. The fact that sorption in the geosphere is lower for certain radionuclides at the higher ionic strength that is expected to prevail during the first 1,000 years is taken into account in the assessment.

Complexing agents

Chemicals contained in the waste may have a complexing capability, and degradation of materials in the repository, such as alkaline degradation of cellulose, can generate complexing agents. If the repository contains high concentrations of complexing agents, sorption of radionuclides in waste matrices and surrounding engineered barriers of concrete may be affected, since the radionuclides can form soluble complexes instead of sorbing on the solid cement surfaces. A review has been made of potential complexing agents that are present, or can be formed, in SFR 1 /Fanger et al. 2001/.

The waste contains chemicals, especially ones used for decontamination at the nuclear power plants, such as tensides and acids, that can act as complexing agents (complexants). The most important chemicals are EDTA (ethylene diamine tetraacetic acid, ethylene diamine tetraacetate), NTA (nitrolotriacetate, nitrilotriacetic acid), citric acid, oxalic acid and Na-gluconate. Under the conditions with high pH that prevail in the concrete pore water, all of these acids become protonated and turn into their salts instead, i.e. citrate, oxalate etc. EDTA has been found to affect the sorption of Ni, Mn and Pb if the concentration of EDTA is sufficiently high (greater than 10^{-4} M) /Bradbury and Sarrott 1994/. NTA and citrate can also affect these radionuclides at very high concentrations (greater than 10^{-2} M). Sorption of other elements (Cs, Pu, Am, U and others) was not affected at concentrations less than or equal to 0.1 M by EDTA, NTA or citrate /Bradbury and Sarrott 1994/. Gluconate has been shown to have some influence on the sorption of Eu /Nordén and Allard 1994, Bradbury and Van Loon 1998/. Oxalic acid did not affect sorption for any of the studied nuclides at the highest concentration in the experiment, 0.1 M /Bradbury and Sarrott 1994/. The concentration of the chemicals inside the waste packages has been calculated based on estimated quantities of chemicals in different waste types in SFR 1 /Fanger et al. 2001/. The concentrations are consistently low; the concentration of EDTA in a few steel drums with cement-stabilized waste (S.09) could possibly be so high that the sorption of divalent ions (Ni, Pb, Mn) could be affected.

Degradation of cellulose in an alkaline environment can give rise to isosaccharinic acid (ISA). If the concentration of ISA is higher than 10^{-4}–10^{-3}, this affects the sorption of tri- and tetravalent radionuclides (EU, Am, cm, Th, Np, Pa, Pu, U, Tc, Zr and Nb) on cementitious materials /Fanger et al. 2001/.Divalent radionuclides (Ni, Co, Fe, Be and Pb) are only affected if the concentration of ISA is higher than 10^{-2} M /Van Loon and Glaus 1998/. The concentration of ISA inside the waste packages has been calculated based on estimated quantities of cellulose materials in different waste types in SFR 1 /Fanger et al. 2001/. The results below are based on the degradation of approximately 2.6% of the quantity of cellulose during the first thousand years.

The calculated concentrations show that a few waste types (F.17, F.23 steel and S.21 in BMA and S.22 in the silo repository[1]) can give rise to such high concentrations of complexing agents (greater than 10^{-4} M) inside the waste packages that some impact on the sorption of tri- and

[1] F.17 contains ion exchangers, filter aids and evaporator concentrate solidified in bitumen. F.23 contains iron/steel, aluminium, cellulose and other organic material solidified in cement. S.21 and S.22 contain iron/steel, aluminium, cellulose and other organic material embedded in cement.

tetravalent nuclides there cannot be ruled out. According to a current waste forecast /Almkvist and Gordon 2007/, the two waste types with potentially the highest concentration of complexants (S.21 and S.22) will not end up in SFR 1. The possible impact of ISA on sorption at the ISA concentrations calculated for this period is so small that it is covered by the choice of Kd values made for cement/concrete /SKB 2001c/. These data are used in the deterministic calculations of radionuclide transport in the main scenario /Thomson et al. 2008a/.

Microorganisms degrade organic materials. The end products are in principle simple organic (e.g. acetate, simple alcohols) or inorganic (e.g. carbon dioxide/bicarbonate/carbonate) molecules. These substances could have complexing properties. Microorganisms can also use organic compounds as an energy source and reduce the quantity of organic complexing agents. In view of the fact that SFR 1 is not an optimal environment for microbial activity, both processes are deemed to be of subordinate importance compared with the formation of complexants from alkaline degradation of cellulose.

Degradation of ion exchange resins can give products with complexing properties. Alkaline hydrolysis of anion exchange resins can give rise to amines with complexing properties /Allard et al. 1985/. Degradation of cation exchange resins gives oxalic acid (or oxalate) as the main degradation product /Allard et al. 1985/. According to a number of investigations, these degradation products from ion exchange resins have no significant impact on the sorption of radionuclides on concrete materials /Bradbury and Sarrott 1994, Bradbury and Van Loon 1998, Allard et al. 1985/. Sulphate and oxalate can be formed in connection with the radiolytic degradation of ion exchange resins /Van loon and Hummel 1999/. Sulphate is expected to form ettringite on reaction with cement and concrete /Höglund 1989/. Oxalate affects the sorption of metals under neutral to acid conditions. Under the conditions prevailing in a concrete environment, the effect is limited due in part to the fact that the hydroxide ions compete with oxalate regarding complexation and in part to the fact that oxalate is precipitated as calcium oxalate.

Radiolytic degradation of bitumen at high pHs has been shown to result in primarily mono- and dicarboxyl acids and carbonates /Van Loon and Kopajtic 1991/. Of these, oxalate could be a potential complexing agent, but it is deemed to be negligible in a concrete environment (as explained above). Furthermore, the radiation is deemed to be too low, except in the most radioactive packages, to give any radiolytic degradation of bitumen /Pettersson and Elert 2001/.

Colloids

The quantity and type of colloids/particles in the water in the barriers can affect the mobility of the radionuclides by acting as carriers. The presence of colloids in the water is due to the water's content of dissolved salts and above all the concentration of positive ions that destabilize the colloids. The colloid content is negligibly small in groundwater where the concentration of calcium ions is greater than 10^{-3} M (40 mg/l) /SKB 2006f/. Because the inflowing saline groundwater has a much higher content of calcium ions (see Table 6-5), the concentration of colloids in this water should be low. Leaching of concrete also contributes dissolved salts, which should further hinder the formation of colloids in those repository parts that have concrete barriers /Hunter 1987/. This assumption is supported by the analyses that have been done of the groundwater in Maqarin in Jordan /Smellie 1998/. The groundwater in Maqarin has a pH of about 12.5 and a composition that otherwise resembles leachate from concrete. The colloid concentrations in this water are very low. Experimental results support the conclusion that at the low colloid concentrations that are obtained in alkaline cement pore water, sorption is negligible, even for strongly sorbing nuclides /Wieland et al. 2004/.

The conclusion is that the water in the barriers in the silo repository and the BMA and BTF repositories contain negligibly small quantities of colloids during this period, i.e. the first 1,000 years. The reason is that the concrete contributes to maintaining high calcium concentrations. Furthermore, the saline groundwater itself has a calcium content that should be sufficiently high to counteract extensive colloid formation. This suggests that the presence of colloids in the water in BLA should also be low.

Chemical interaction between different rock vaults

The chemical interaction that can take place between the different rock vaults mainly has a bearing on the propagation of high pH from the BMA and BTF repositories and the possible importance this may have for the degradation of organic material in BLA and the generation of potentially strong complexing agents such as ISA. However it does not appear probable that the input of hydroxide ions to BLA from other rock vaults will be so great that alkaline hydrolysis of the organic material in BLA will be of importance. This judgement is based on the small hydraulic contact between the rock vaults and the fact that the propagation of high pH will be delayed due to reactions with gravel backfill and with minerals in the rock between the rock vaults. If such conditions should nevertheless arise in BLA that the organic material is subjected to alkaline hydrolysis that produces ISA, this should nevertheless be of subordinate importance for the release of radionuclides in other repository parts. The reason for this is the absence of flow paths from BLA to the other rock vaults, see section 6.4.2. Possible transport of ISA or other loose organic material from BLA to the other repository parts must then take place via diffusion through intervening rock.

Even if flow paths should for some reason form in the future from BLA to the BMA or BTF repositories, this is judged to be of minor importance for the release of radionuclides from BMA or BTF. If ISA is formed in BLA and is transported to BMA or BTF, this ISA will be retained by sorption in the outer parts of the concrete barriers there. Transport of cellulose in the form of particles or fibres from BLA to the other rock vaults, where the cellulose is then degraded to ISA, is not expected to be of importance either. If such transport takes place at all, the quantities of cellulose that are moved from BLA to another rock vault should be negligibly small.

Gas formation

Gas can be formed in the repository by corrosion of metals in the waste, in waste packaging and in the reinforcing bar in concrete structures, as well as by microbial degradation of organic material in the waste. Radiation from the radioactive waste can also generate gas by means of radiolysis of water.

Large quantities of gas can potentially be formed in a repository for low- and intermediate-level waste. In order for the gas to get out into the surrounding rock, gas-conducting passages must be created in the repository. Possible consequences of the pressure build-up that is required to create these passages is cracking of repository barriers and displacement of contaminated water, plus increased release of radionuclides.

When the repository is closed and pumping ceases, the lower pressure in the repository will allow groundwater to flow in. Total saturation of the silo repository takes around 25 years, while other parts of the repository are saturated in just a few years /Holmén and Stigsson 2001a/. Remaining atmospheric oxygen and oxygen dissolved in water in the repository will be consumed by aerobic corrosion or some other oxygen-consuming process such as microbial degradation. Aerobic conditions are therefore only expected to prevail for a short time. Anaerobic conditions will first develop locally and then gradually spread until anaerobic conditions prevail in the whole repository.

Gas formation due to corrosion

When the oxygen in the repository has been consumed, hydrogen gas can be formed by anaerobic corrosion, which is the process that is expected to contribute the largest quantities of gas in low- and intermediate-level repositories. A prerequisite for hydrogen-generating corrosion is a supply of water. This is rarely a limiting factor in an underground repository, and even the initial content of water in the waste and the engineered barriers is often sufficient to generate gas. Theoretically, approximately 1 litre of water is needed to generate 1 Nm^3 of hydrogen.

Another factor that affects corrosion is water chemistry – mainly pH, Eh and the concentration of dissolved salts. Temperature and radiation level can be of importance for repositories with high-level waste, but are of little importance for repositories with low- and intermediate-level waste. It has also been found that the high pressures that are required in order for the hydrogen gas pressure to significantly inhibit the corrosion rate exceed the pressures needed for the gas to get through the surrounding barriers /Moreno et al. 2001/.

A compilation of corrosion rates under conditions similar to those in SFR 1 shows corrosion rates for iron and steel in the range 0.1–10 µm/year /Moreno et al. 2001/. In the gas formation calculations /Moreno et al. 2001/, a corrosion rate for iron and steel of 1 µm/year has been assumed, corresponding to a production of hydrogen gas of approximately 3 litres/m^2·year and total corrosion of a 5 mm plate in 2,500 years. The corrosion rate for aluminium and zinc has been assumed to be 1 mm/year, corresponding to corrosion of all material within a few years. A status report from the European Commission on gas migration and two-phase flow for a deep repository provides an overview of studies and experiments published within the area of gas generation prior to January 1999 /Rodwell et al. 1999/. The compiled gas formation rates for different materials and environments are in accordance with the assumed corrosion rates.

Gas formation due to microbial degradation of material

Microbial degradation of organic material can take place under both aerobic and anaerobic conditions. Under aerobic conditions, oxygen is consumed and carbon compounds are broken down to carbon compounds with a lower molecular weight. The end products are carbon dioxide and water. In anaerobic degradation, different inorganic sources such as nitrate and sulphate are used as oxidants instead of oxygen. Water, nutrients and certain trace elements are required in order for degradation to take place. In anaerobic degradation, a number of intermediate products are formed such as alcohols and organic acids. The end products of anaerobic degradation are hydrogen gas, methane and carbon dioxide. The chemical environment (pH and salinity) and other factors such as temperature, pressure and radiation level are of importance for the rate of microbial degradation. However, investigations have shown that microorganisms have a remarkable ability to adapt to most environments. Of the organic materials found in the repository such as ion exchange resins, bitumen and cellulose, cellulose is the material that is expected to have the highest degradation rate.

Microbial degradation of organic materials under conditions expected to prevail in SFR 1 after closure has been investigated by /Pedersen 2001/. Experiments cited there indicate that gas formation is initially fast but decreases after the initial phase. According to Pedersen, the environment in SFR 1 is not optimal for microbial degradation, but even as high a pH as 12 is no obstacle to microbial activity. Gas formation due to microbial activity in SFR 1 could be limited by the supply of oxidants and nutrients and the removal of reaction products. A possible positive aspects that could limit the total gas formation in the repository is that many microorganisms can utilize hydrogen as an energy source and could thereby reduce the quantity of hydrogen formed by corrosion. This process, which is considered favourable, has not been included in the assessment, however.

Cellulose degradation rates corresponding to complete consumption in less than 200 years have been assumed in the calculations of gas formation by microbial degradation. This is equivalent to a degradation rate of 0.2 mol/kg·year and a gas formation rate of about 2 l/kg·year, assuming that 50% of the gases are inert /Moreno et al. 2001/.

The few experiments that have been done on microbial degradation of bitumen, ion exchange resins and plastics indicate that the processes are very slow. In the calculations it has been assumed that 0.002 mole/kg·year is degraded, corresponding to a degradation of all material in 15,000 years and a gas formation rate of 0.02 l/kg·year, assuming that 50% of the gases are inert /Moreno et al. 2001/.

Gas formation due to radiolysis

Radiation from the radioactive waste in SFR 1 can affect materials, which can lead to formation of gas and species that can affect the water chemistry. This process is called radiolysis. The materials in the waste and the immediate environs will be exposed to the greatest amount of radiation. G-values, which express the number of molecules formed due to irradiation, are used in calculating gas formation due to radiolysis. G-values have been determined experimentally for various materials and types of radiation. The effect of irradiation is proportional to the absorbed dose and dependent on the composition and water content of the material. Inorganic materials are often more stable than organic ones. In the simplified calculations of gas formation due to radiolysis, G-values for water have been assumed and also that all the energy is absorbed in the water present in the ion exchange resins, the conditioning material and the surrounding material /Moreno et al. 2001/.

Calculated gas quantities

The quantity of gas that can be formed in SFR 1 was previously estimated by /Moreno et al. 2001/. Since a new prediction of the material quantities in the waste has been made /Almkvist and Gordon 2007/, the estimate of the quantity of gas that can form has been updated. This update is presented only in this report. The new estimate has been made in the same way as in /Moreno et al. 2001/ and as described above, but with the updated figures on material quantities[2]. The theoretical initial gas formation rate is presented in Table 6-7, and the total quantity of gas formed in 100,000 years is presented in Table 6-8.

The gas formation rate is dominated initially by the quantity of gas that is formed by corrosion of aluminium and zinc. The quantity of aluminium in the silo repository is, however, so low that gas formation is initially dominated by steel corrosion. It was assumed in the SAFE project that the waste type S.22 (scrap metal and refuse from Studsvik), with a large quantity of aluminium, would be deposited in the silo repository /Riggare and Johansson 2001/. None of this waste has been deposited in the silo, and there are no longer any plans for such deposition. This means that the initial gas formation rates calculated here for aluminium in the silo repository are much lower than they were in the SAFE project.

After a few years steel corrosion dominates, since aluminium and zinc are quickly consumed. Hydrogen-evolving steel corrosion is also the process that makes the largest contribution to the total gas quantity formed in the different repository parts.

Table 6-7. Theoretical initial gas formation rate [Nm³/year] in SFR 1 from different materials in waste, waste packaging and structures.

	Silo	BMA	1BTF	2BTF	BLA
Corrosion					
Steel	770	580	300	190	960
Al + Zn	380	3,500	21,000	1,600	32,000
Microbially					
Cellulose	18	330	4	0.4	1,000
Other organic waste	1	7	0.4	1	35
Resins + bitumen	85	77	12	18	5
Radiolysis	3	0.02	0.02	0.2	0.002

[2] Almkvist and Gordon provide data for three different inventories: operation for 50 years, operation for 60 years and full repository. The gas calculations have been done for the material quantities for full repository as regards volume of waste. The data on reinforcing bar in the structures are from /Moreno et al. 2001/.

Table 6-8. Total gas volumes formed [Nm³] in SFR 1 from different materials in waste, waste packaging and structures.

	Silo	BMA	1BTF	2BTF	BLA
Corrosion					
Steel	2,300,000	1,700,000	520,000	480,000	2,100,000
Al + Zn	750	9,000	43,000	3,200	81,000
Microbially					
Cellulose	3,300	61,000	700	69	190,000
Other organic waste	14,000	98,000	5,300	20,000	520,000
Resins + bitumen	1,300,000	1,200,000	180,000	270,000	72,000
Radiolysis					
0–100,000 years	150	2	2	10	1

Microbial degradation of cellulose contributes to the gas formation rate during the first hundred years in above all BLA and BMA. The waste contains large quantities of organic material in the form of ion exchange resins and bitumen. Microbial degradation of these materials is probably a very slow process limited by the conditions in the waste and the repository.

Radiolysis generates comparatively small quantities of gas and primarily during a timespan of 20 years, during which time the gas formation rate declines steadily. The silo repository is the repository part that contains the most radioactive waste in SFR 1, and it is therefore here that the largest quantities of radiolysis gas are formed.

The impact of gas formation on radionuclide release via gas-driven advection from the silo repository is studied in one of the scenarios, see Chapter 7.

Gas transport

In order for the gas formed in waste packages and concrete structures in the repository to escape, gas-conducting passages must be formed in the barriers. The gas transport and the quantity of water expelled from the silo repository and the rock vaults are determined by the design of the barriers and the properties of the barrier materials.

In materials with a fine pore structure such as concrete, capillary forces are of importance for the pressure that needs to be built up to expel the gas. Water will be expelled from the concrete until a network of empty pores has been formed for transport of the gas. When gas-conducting passages have been formed in the barrier, the gas flows out as long as the pressure difference exceeds the capillary pressure. The capillary pressure in an intact structural concrete is of the order 1-2 MPa /Moreno and Neretnieks 1991/. If the structural concrete has small cracks, much less pressure is required to expel the gas. A pressure of 1–2 kPa is required for a planar crack with an aperture of 0.1 mm, while a pressure of about 15 kPa is required for a 10 µm crack /Moreno et al. 2001/. In concrete packages and concrete structures, a number of small cracks is sufficient to expel all the gas.

In the silo repository, the waste is surrounded by a porous concrete with low resistance to gas transport. Only a small gas pressure is required to open up gas passages in this concrete, and the quantity of water that is expelled has been measured experimentally to be 0.1–2% of the pore volume /Björkenstam 1997/. It has been assumed in the gas transport calculations that 2% of the pore volume in the concrete can be displaced. In order for the gas to find its way out through the gas evacuation pipes and the sand/bentonite barrier in the top, a gas pressure must be built up in the concrete silo equivalent to the opening pressure of the sand/bentonite barrier. Experiments show that a pressure of approximately 15 kPa is required to achieve gas transport through the sand/bentonite and that the expelled water is only a few tenths of a percent of the total pore volume /Pusch and Hökmark 1987/.

In a gravel fill, only small pressures are required to open up transport pathways and to drive the gas through the porosity in the fill. Gas that has flowed through gravel fill and arrived at the void underneath the roof in the silo repository and the rock vaults can then be further transported in fractures in the surrounding rock.

The transport capacity for gas in the rock in the repository area has been calculated. The results show that the fracture system that normally exists in the rock has a high transport capacity and that a few fractures are sufficient to remove the gas quantities that can be generated in the repository /Thunvik and Braester 1986/. This result is also supported by more recent studies of gas transport in fractured rock. The gas breakthrough occurs quickly and gas is transported through the more permeable fractures, while the fluid in the fractures with lower permeability is almost stagnant /Berger and Braester 2000/.

SKB's research on gas transport has been focused on Lasgit /Sellin and Harrington 2006/ in the Äspö HRL. Lasgit (Large-Scale Gas Injection Test) is a full-scale experiment with KBS-3V geometry for studying the effect of gas transport in the bentonite buffer. Gas began to be injected in Lasgit in the spring of 2007. This could provide preliminary results regarding how the gas build-up and transport processes take place. Since the bentonite buffer has not reached its equilibrium state, however, the results from the first test series must be treated with some caution.

How gas is transported in the engineered barriers in a repository for intermediate-level waste has been studied on a field scale in the Gas Migration Test (GMT) /Shimura et al. 2006/. The test started in 1997 in Nagra's underground laboratory in Grimsel, Switzerland. The field tests were concluded in 2004 and most of the evaluations and modellings have also been concluded. The test was conducted in a special-purpose concrete silo with a bentonite/sand barrier fitted with a gas valve. Two phases of gas tests were conducted in GMT. Before, between and after the gas tests, hydraulic tests were performed to see whether the properties of the engineered barriers were altered due to the gas breakthroughs. The following conclusions were drawn from the GMT tests:

- Gas could be transported through the valve to the geosphere at relatively high flows and low pressures.
- The function of the bentonite/sand barrier was not adversely affected by the gas. No change could be detected in the hydraulic properties.

The volume of water that was expelled from the silo during the gas tests was very small (10–13 litres, about 1% of the total injected gas volume).

The contribution of gas formation to radionuclide release via gas-driven advection from the silo repository is studied in one of the scenarios, see Chapter 7.

6.4.5 Status of safety functions for the period during the first 1,000 years after closure

A number of safety functions and safety performance indicators have been defined for the safety assessment, see Chapter 5. Safety functions and safety performance indicators are tools for analyzing the future performance of the repository and for arriving at a complete set of scenarios. The safety functions defined for SFR 1 during the period in question are examined below to determine whether the safety function remains unchanged or whether it changes, and if so how. Uncertainties and deviations from the above-described status of the safety functions comprise one of the cornerstones of scenario selection in Chapter 7.

Low flow in repository parts

The safety function "low flow in repository parts" is judged with the aid of two performance indicators: fracture transmissivity and hydraulic gradient in surrounding rock. It is noted in section 6.4.2 that the site for SFR 1 was selected in part because it is situated in an area with a limited hydraulic gradient and limited fracture transmissivity. The fracture transmissivity can be changed by chemical reactions in the fractures, but these changes are judged to be very slow during the period. Greater changes in fracture transmissivity can be expected in conjunction with earthquakes, which is dealt with in scenario selection, see Chapter 7. Shoreline displacement causes the hydraulic gradient to increase slightly during the period. The change in the hydraulic gradient is reflected in the regional flow, which has been calculated to be 3 litres/m^2·year at closure and 5 litres/m^2·year after 1,000 years /Holmén and Stigsson 2001a/, see section 6.4.2.

Limited advective transport in concrete and bentonite barriers

The safety function "limited advective transport" has been chosen for the hydraulic function of the engineered barriers. The safety function entails limited advective transport through the concrete in the BMA and BTF repositories and limited advective transport through the bentonite in the silo repository.

The concrete barriers

Three indicators have been chosen to assess how the safety function of the concrete barriers develops with time: hydraulic conductivity of concrete tanks in BTF, hydraulic conductivity of concrete walls in BMA and temperature in the concrete barriers.

Hydraulic conductivity of concrete tanks in BTF – According to the description in section 6.4.4 of the mechanical and chemical processes, they will somewhat affect porosity and fracture frequency, which in turn affects the conductivity of the concrete. According to the data report for the SAFE project /SKB 2001c/, the value of the hydraulic conductivity, $8.3 \cdot 10^{-10}$ m/s, is representative for structural concrete with some small penetrating cracks. This value has been used for the concrete tanks in BTF in the hydrogeological calculations for the first 1,000 years, see section 6.4.2.

Hydraulic conductivity of concrete walls in BMA – Se "Hydraulic conductivity of concrete tanks in BTF".

Temperature in the concrete – According to the description in section 6.4.1, the temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn controlled by prevailing climatic conditions. The climate changes are not so great that the temperature in the repository could fall to 0°C, which ensures that the concrete will not freeze.

Thus, no great changes are expected during the first 1,000 years in the advective transport in the concrete barriers in BTF and BMA.

The bentonite barrier

Three indicators have been chosen to assess how the safety function of the concrete barrier develops over time: hydraulic conductivity of bentonite, temperature and gas pressure in the silo. The status of these safety performance indicators during the period is presented below.

Hydraulic conductivity of bentonite – The hydraulic conductivity of the bentonite is affected very slowly by the chemical reactions that occur, see the description in section 6.4.4. No other processes are expected to occur that have any significant impact on the hydraulic conductivity of the bentonite during the first 1,000 years. According to the data report for the

SAFE project /SKB 2001c/, the value of the hydraulic conductivity of bentonite, $6 \cdot 10^{-12}$ m/s, is representative for intact barriers for 10,000 years. This value of the hydraulic conductivity means that transport through the bentonite barrier is controlled by diffusion. The value has been used in the hydrogeological calculations that are presented in section 6.4.2.

Temperature – According to the description in section 6.4.1, the temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn governed by prevailing climatic conditions. The climate changes are not so great that the temperature in the repository could fall to –5°C, which is the temperature required for the bentonite barriers to freeze.

Gas pressure in the silo – According to the description in section 6.4.4, only a small gas pressure is required for gas to be transported through concrete packages, porous concrete and the concrete structure. In order for the gas to find its way out through the gas evacuation pipes and the sand/bentonite barrier in the top, a gas pressure must be built up equivalent to the opening pressure of the sand/bentonite barrier, which is around 15 kPa. The chemical reactions that are expected during the first 1,000 years are not expected to lead to such great changes in the opening pressure of the sand/bentonite barrier that the gas pressure will be higher than around 15 kPa.

The safety function "limited advective transport in the bentonite barrier" will be largely unchanged and transport through the bentonite is expected to be controlled by diffusion during at least the first 1,000 years.

Good sorption in concrete barriers

A review of the safety performance indicators for good sorption in concrete has been done in section 6.4.4 and is summarized below.

High pH – Degradation of the concrete barriers is judged to be so slow that a high pH will be maintained in the concrete barriers during the period in question.

Reducing conditions – Corrosion of iron and microbial processes will certainly provide a reducing environment in the repository during this period.

Low concentrations of complexing agents – A limited initial quantity of complexing agents is ensured by SKB's and the regulatory authorities' inspections during the operating phase. In addition to the initial quantity of complexing agents, additional complexants will be produced by degradation of organic material. The predicted concentration of complexing agents during the period is so low (see section 6.4.4) that sorption is not affected to a greater extent than is included in the uncertainties for the selected sorption data.

Available sorption surface area – Concrete has a large specific surface area, which favours sorption. Degradation of the concrete barriers is so slow that a large available sorption surface area will be maintained during the period.

The indicators show that the safety function "good sorption in concrete barriers" does not change appreciably during the period.

No wells

The safety function "no wells" has the performance indicator "location in relation to shoreline". It is stated in section 6.2.1 about shoreline displacement that the shoreline will pass the repository in about a thousand years, which means that no wells are expected to be drilled during the period.

6.5 Evolution of the repository during the period from 3,000 AD to 20,000 AD

The period from 3,000 AD to 20,000 AD is dominated by a temperate climate with shorter periods of permafrost that reaches down to a maximum depth of about 50 m in the rock, see Figure 6-3. Due to shoreline displacement the repository is no longer beneath the sea, see section 6.2.1.

The activity in the waste decays, and at 20,000 AD it is less than 1% of what it was at closure. At the beginning of the period, in 3,000 AD, the activity consists primarily of inorganic C-14, Ni-59 and organic C-14. At the end of the period the same three nuclides still dominate, but the activity of C-14 has declined so that it is less than 10% of the activity of C-14 at closure.

6.5.1 Thermal evolution

According to the climate evolution based on the latest glacial cycle, the first near-surface permafrost occurs in around 10,000 AD. As the permafrost spreads the rock will consist of both frozen and unfrozen rock. At around 10,000 AD the permafrost reaches down about 50 m in the rock, which is almost to repository depth, which is around 60 m, see Figure 6-3 and Figure 6-22. The concrete and the bentonite do not freeze entirely at 0°C; the fraction of the water that freezes increases as the temperature falls. The water in the smallest pores in the bentonite does not freeze until the temperature falls below –5°C, while the concrete freezes at a slightly higher temperature /Emborg et al. 2007/.

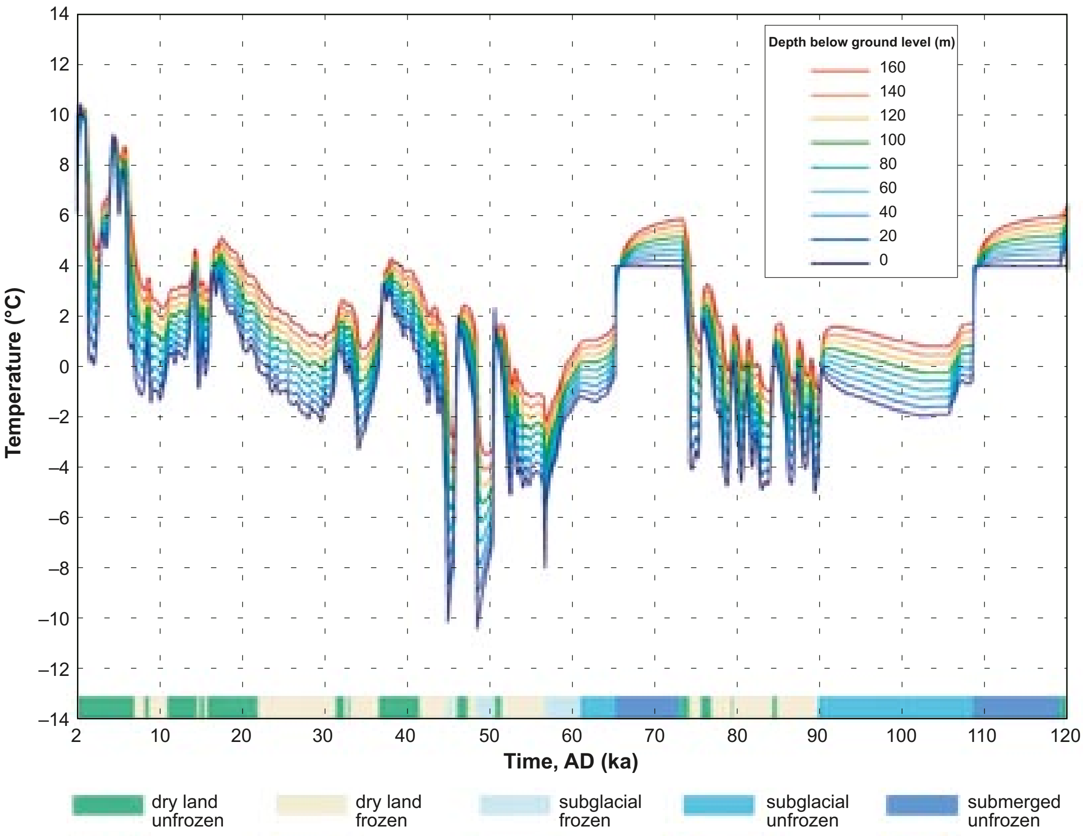


Figure 6-22. Change in the temperature at the ground surface and in the rock for the climate evolution based on the latest glacial cycle /Vidstrand et al. 2007/.

6.5.2 Hydrogeological evolution

The shoreline has passed SFR 1 and the local groundwater system is evolving towards a steady-state situation that is controlled by the local topography. When conditions are steady-state, the groundwater flow in the rock and the repository at SFR 1 do not change with time. The hydrogeological models predict that a steady-state-like situation will be reached in around 5,000 AD /Holmén and Stigsson 2001a/. When the local groundwater system has reached a steady-state situation, shoreline displacement no longer affects the local situation at SFR 1, since the shoreline is then far away.

In roughly 4,800 AD a topographical threshold, which is located at a depth of 15 metres today, gives rise to the formation of lakes and mires about 1 km northeast of the repository.

The first shallow permafrost at around 10,000 AD, in the reference evolution based on the latest glacial cycle, does not penetrate into the repository, which is located at a depth of approximately 60 metres (see Figure 6-3). For this reason there is no appreciable change of the water flow in the repository. In the parts of the rock that freeze, the hydraulic conductivity will decrease and no groundwater flow will occur in frozen parts of the rock during the period with shallow permafrost. Since this only applies to a limited portion of the rock and during a short period of time, freezing of parts of the rock is neglected in the continued description of the hydrological evolution during the period. A generic simulation has been carried out of groundwater flows at SFR 1 under different future climatic conditions, including the first shallow permafrost /Vidstrand et al. 2007/. The results are presented together with the continued hydrogeological evolution for the next period, see section 6.6.2.

Regional groundwater flow and water flow in the silo repository and the rock vaults

A low regional groundwater flow was calculated for this period as well. Simulations with the local hydrogeological model show that the average value for the regional groundwater flow initially increases slightly, after which steady-state conditions set in at 7 litres/m^2·year /Holmén and Stigsson 2001a/.

The water flow in the silo repository and the rock vaults for the period after 1,000 years has been calculated with the same hydrogeological models as for the first 1,000 years /Holmén and Stigsson 2001a, Holmén 2005, Holmén 2007/. Results from the detailed model are presented in Table 6-9 and Figure 6-23. The calculations show that the water flow through the enclosures in both the silo repository and BMA during this entire period is very low. In the BTF repositories, the water flow through the enclosure constitutes up to 26% of the water flow through the whole rock vault, but the water flow through all of the BTF repositories is roughly half of the water flow through all of BMA. The water flow in all of BLA is roughly equal to the water flow in all of BMA, but most of the water flow in BLA goes through the waste domain. The effect of degraded barriers with increased hydraulic conductivity in 1BTF has also been modelled /Holmén and Stigsson 2001a/. The result shows an increase of the water flow through the whole rock vault by approximately a factor of 2. Compared with the case with intact barriers, it is predicted that a larger portion of the water flow will pass through the enclosure.

Uncertainty analysis of water flows in the silo repository and the rock vaults

The uncertainty analysis of water flows in the silo repository and the rock vaults performed with the local model /Holmén 2005/ was described above in section 6.4.2. The results also include probability distributions of water flows in the silo repository and the rock vaults at 4,000 AD, see Figure 6-24.The figure also shows results from previous calculations without uncertainty analysis with the local hydrogeological model /Holmén and Stigsson 2001a/. The difference between the median values for the probability distributions /Holmén 2005/ and the previously calculated values /Holmén and Stigsson 2001a/ are mainly due to the fact that the calibration of the open repository in the latter calculations included a hydraulic skin around the tunnels in the model.

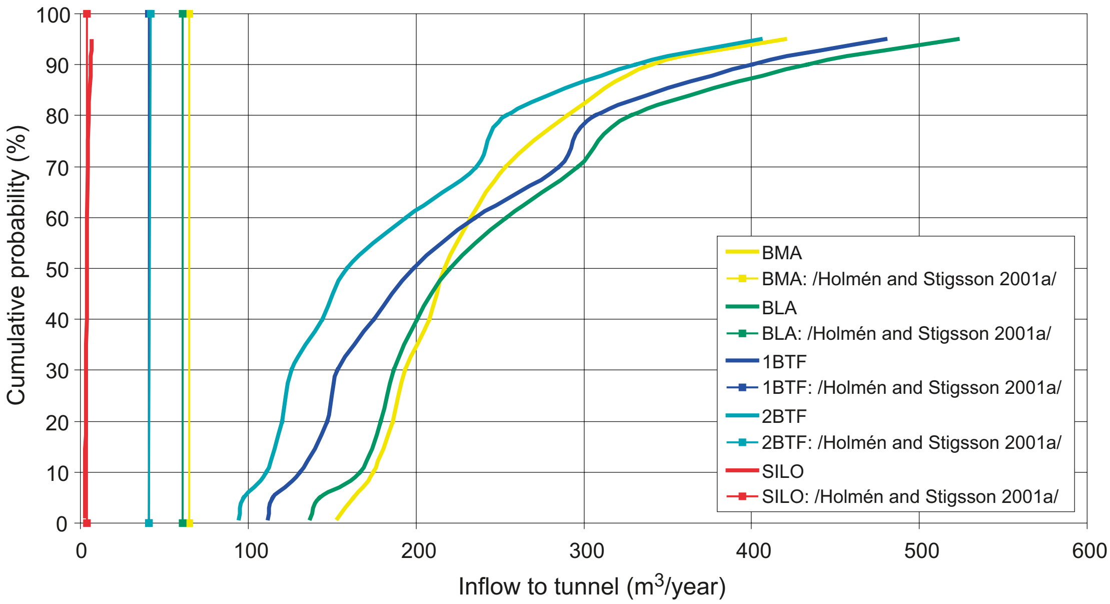


Figure 6-23. *Probability distribution of water flows through the silo repository and the rock vaults in 4,000 AD /Holmén 2005/. For comparison, water flows calculated previously with the local hydrogeological model are also shown /Holmén and Stigsson 2001a/.*

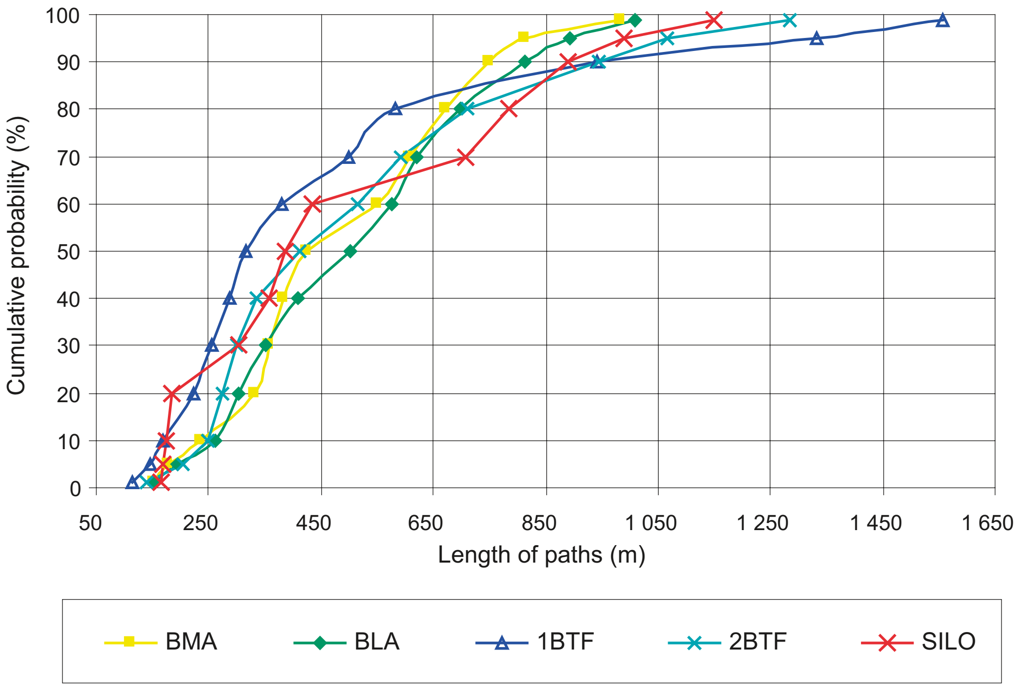


Figure 6-24. *Probability distribution of the length of the flow paths at 5,000 AD (results from /Holmén 2007/).*

Table 6-9. Water flows in the silo repository and the rock vaults at 4,000, 5,000, 6,000 and 7,000 AD calculated with the detailed hydrogeological model /Holmén and Stigsson 2001a/.

	Total flows (m^3/year)			
	4,000 AD	5,000 AD	6,000 AD	7,000 AD
1BTF: Enclosure	6.8	7.8	8.0	8.0
1BTF: Whole rock vault	26.4	30.7	30.4	30.5
2BTF: Enclosure	6.0	6.8	6.9	6.9
2BTF: Whole rock vault	27.7	29.6	29.9	29.9
BLA: Waste domain	35.0	38.4	38.8	38.8
BLA: Whole rock vault	50.2	54.2	54.8	54.9
BMA: Enclosure	0.26	0.28	0.28	0.28
BMA: Whole rock vault	52.7	54.7	54.7	54.7
Silo: Enclosure	0.16	0.23	0.25	0.25
Silo: Top fill	2.2	2.2	2.2	2.2

Water flow between the rock vaults

The dominant flow paths between the rock vaults and the proportion of water that flows along these paths are given below (based on /Holmén and Stigsson 2001b/).

- Water flow from 1BTF to 2BTF. The flow is greatest in 3,000 AD when 10% of the flow from 1BTF passes to 2BTF. From 5,000 AD and onward the flow is 4%.
- Water flow from 2BTF to BLA. The flow is greatest in 4,000 AD when 8% of the flow from 2BTF passes to BLA. From 5,000 AD and onward the flow is 4%.
- Water flow from BMA till BLA. The flow is greatest in 3,000 AD when 6% of the flow from BMA passes to BLA. From 5,000 AD and onward the flow is 3%.

In summary, the hydrogeological calculations show that around 10% of the water flow can pass from one rock vault to another.

Analysis of the flow paths from the repository

When the groundwater's flow direction in the repository's near-field changes (due to shoreline displacement) to a mainly horizontal flow pattern (in roughly 4,000 AD), the flow pattern around the repository becomes more complex and the flow paths become longer. In around 5,000 AD the groundwater flow near the repository becomes steady-state, which means that the flow situation does not change since it is no longer affected by where the sea water level is located /Holmén and Stigsson 2001a/.

Length of flow paths from repository to ground surface

In predictions with the local hydrogeological model, a large number of flow paths were generated from the silo repository and the rock vaults. A statistical analysis of these flow paths was performed, see Table 6-10. A visualization of the flow paths at 4,000 AD and 6,000 AD is shown in Figure 6-25. The uncertainty analysis of the flow paths from the repository was conducted for two points in time: immediately after closure and water saturation and at 5,000 AD /Holmén 2007/. The calculated probability distribution of the length of the flow paths at 5,000 AD is shown in Figure 6-24. The results show that the flow paths become progressively longer at the beginning of the period. At around 5,000 AD, the flow situation becomes steady-state and the length of the flow paths remains unchanged throughout the rest of the period.

Table 6-10. Length of flow paths from the silo repository and the rock vaults (results from /Holmén and Stigsson 2001a/).

Year	Median length of flow paths from silo repository and rock vaults to ground surface [m]				
	BMA	BLA	1BTF	2BTF	Silo
3,000	114	89	125	99	379
4,000	176	308	617	481	341
5,000	206	375	789	584	355
6,000	214	387	785	604	355
7,000	216	387	785	604	355

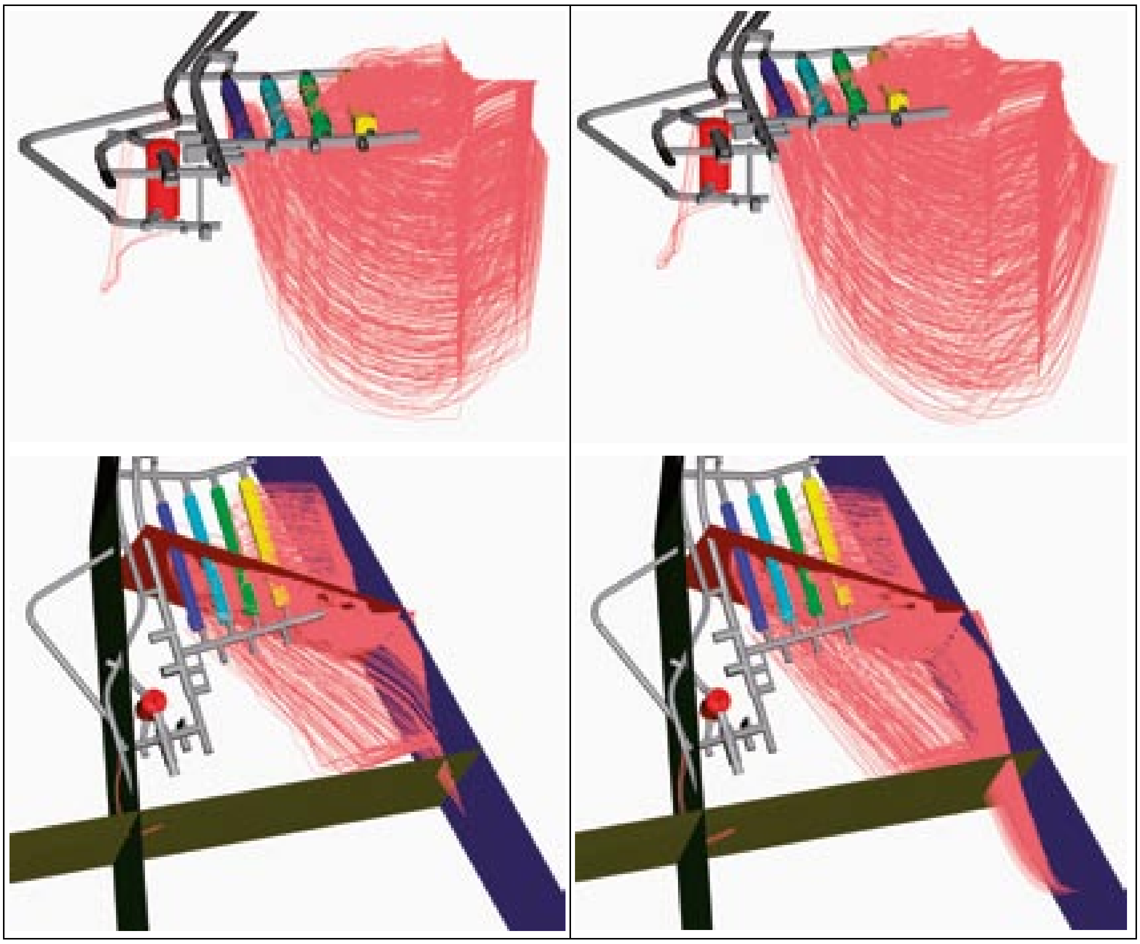


Figure 6-25. *Examples of predicted flow paths from the silo repository and the rock vaults at 4,000 AD (left) and 6,000 AD (right). Outflow takes place mainly along zone 6, above the rock vaults and beneath the sea /Holmén and Stigsson 2001a/.*

Breakthrough times for flow paths from rock vaults to ground surface

A large number of flow paths were generated from each rock vault. A statistical analysis of these paths gives results as shown in Table 6-11 /Holmén and Stigsson 2001a/, and the results of the uncertainty analysis at 5,000 AD are shown in Figure 6-26 /Holmén 2007/. The results show that the breakthrough times become progressively longer at the beginning of the period. The flow situation becomes steady-state at around 5,000 AD, and the breakthrough times remain unchanged throughout the rest of the period.

Table 6-11. Median values of breakthrough times for flow paths from the silo repository and the rock vaults (results from /Holmén and Stigsson 2001a/).

Year	Breakthrough time [years]				
	BMA	BLA	1BTF	2BTF	Silo
3,000	52	18	119	44	379
4,000	74	87	384	214	121
5,000	84	127	491	286	129
6,000	86	137	521	297	131
7,000	87	137	521	303	131

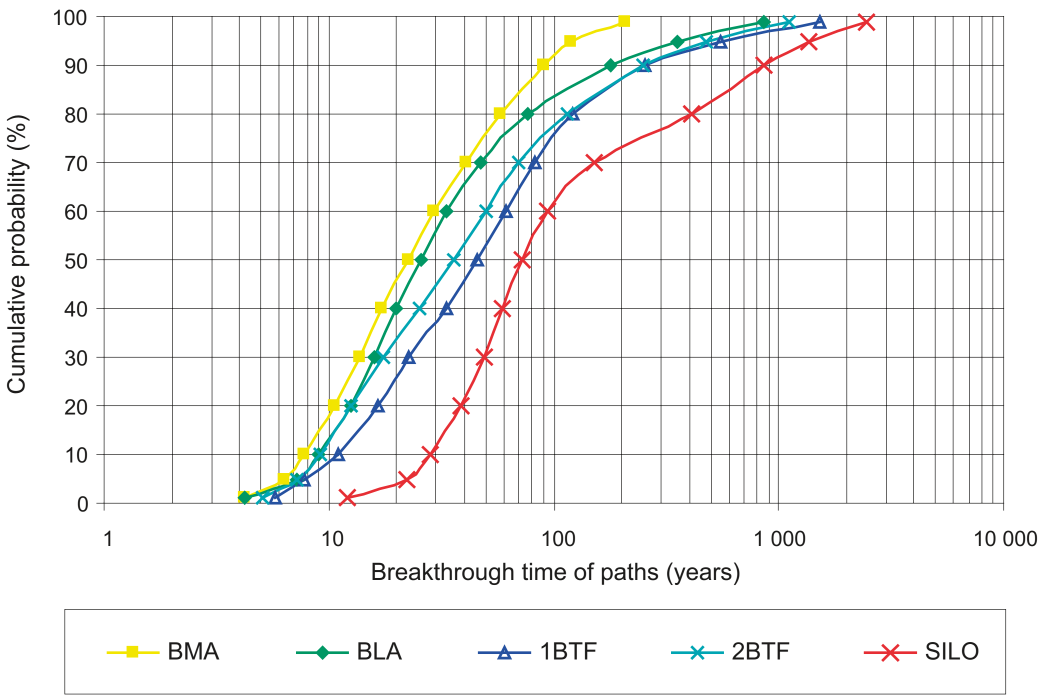


__Figure 6-26.__ Probability distribution of breakthrough times for the flow paths at 5,000 AD (results from /Holmén 2007/).

Flow paths in fracture zones from the repository

The geological-structural interpretation of the rock mass around SFR 1 is presented briefly in section 4.8.3. There are four local zones, numbered 3, 6, 8 and 9. These zones are subvertical. In addition there are two regional zones near the repository, the subhorizontal zone H2 and the subvertical Singö Zone. Zone 6 intersects the four rock vaults (1BTF, 2BTF, BLA and BMA). Zone H2 lies subhorizontally beneath the repository, while the other local zones lie around the repository. The fracture zones around the repository are shown in Figure 4-12.

Initially, zone 6 is the only zone of importance. There are no flow paths in any other zones. At 3,000 AD, zones H2, 3, 8 and 9 are also important flow paths from the rock vaults. This is a consequence of the fact that the groundwater's flow pattern changes with time due to shoreline displacement. The fracture zones that are of importance for the flow paths from the rock vaults when steady-state conditions have been achieved (5,000 AD) are:

- BMA – zones 3, 6 and H2, and to a very slight degree zone 8.
- BLA – zones 6, 3 and H2, and to a slight degree zone 8.
- 1BTF and 2BTF – zones 8, 6, 3 and H2.

Discharge areas for flow paths from the rock vaults

The locations of the discharge areas at 4,000 AD and 5,000 AD are presented in Figure 6-27 /Holmén and Stigsson 2001a/. The results of the uncertainty analysis for 5,000 AD /Holmén 2007/ shows a slightly greater spread, see Figure 6-28.

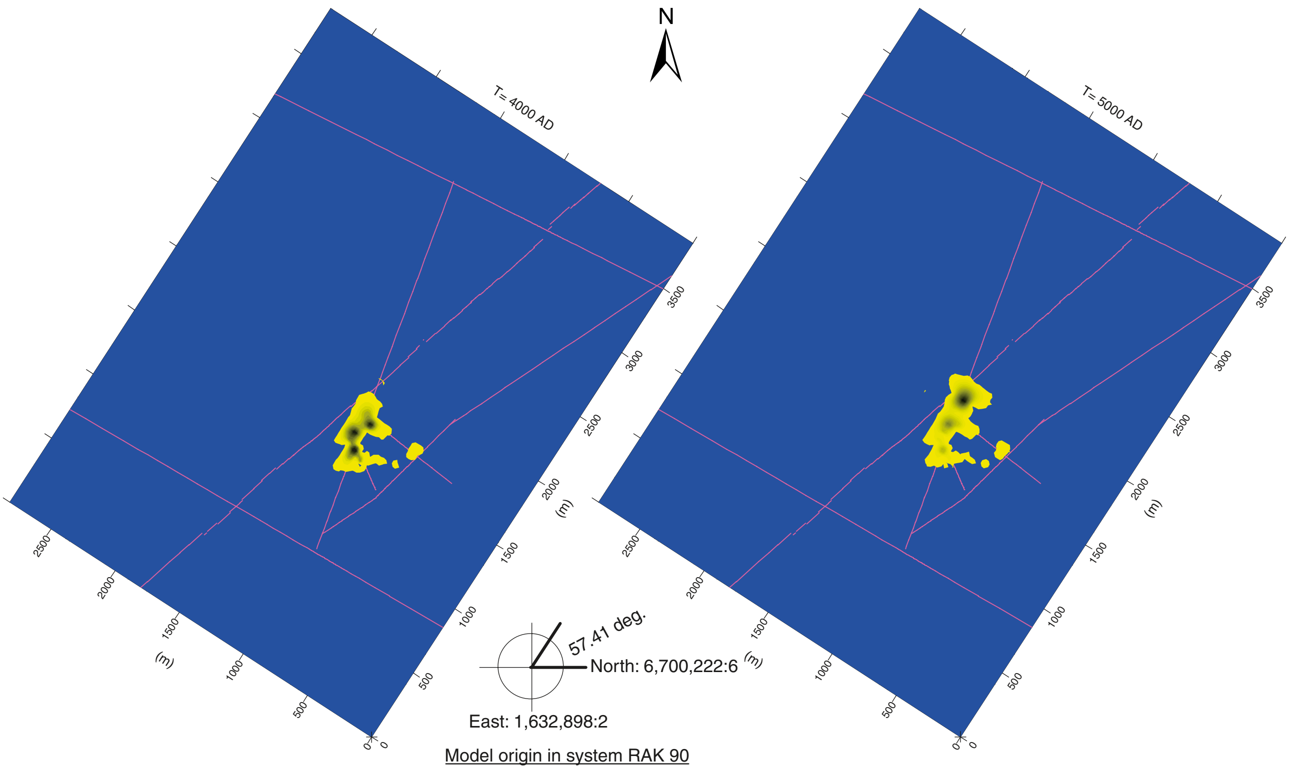


Figure 6-27. Predicted discharge areas for the water flow from the silo repository and the rock vaults at 4,000 AD (left) and at 5,000 AD (right). The yellow areas mark the location of the discharge areas. The repository with access ramp is marked with small squares and the fracture zones are pink /Holmén and Stigsson 2001a/.

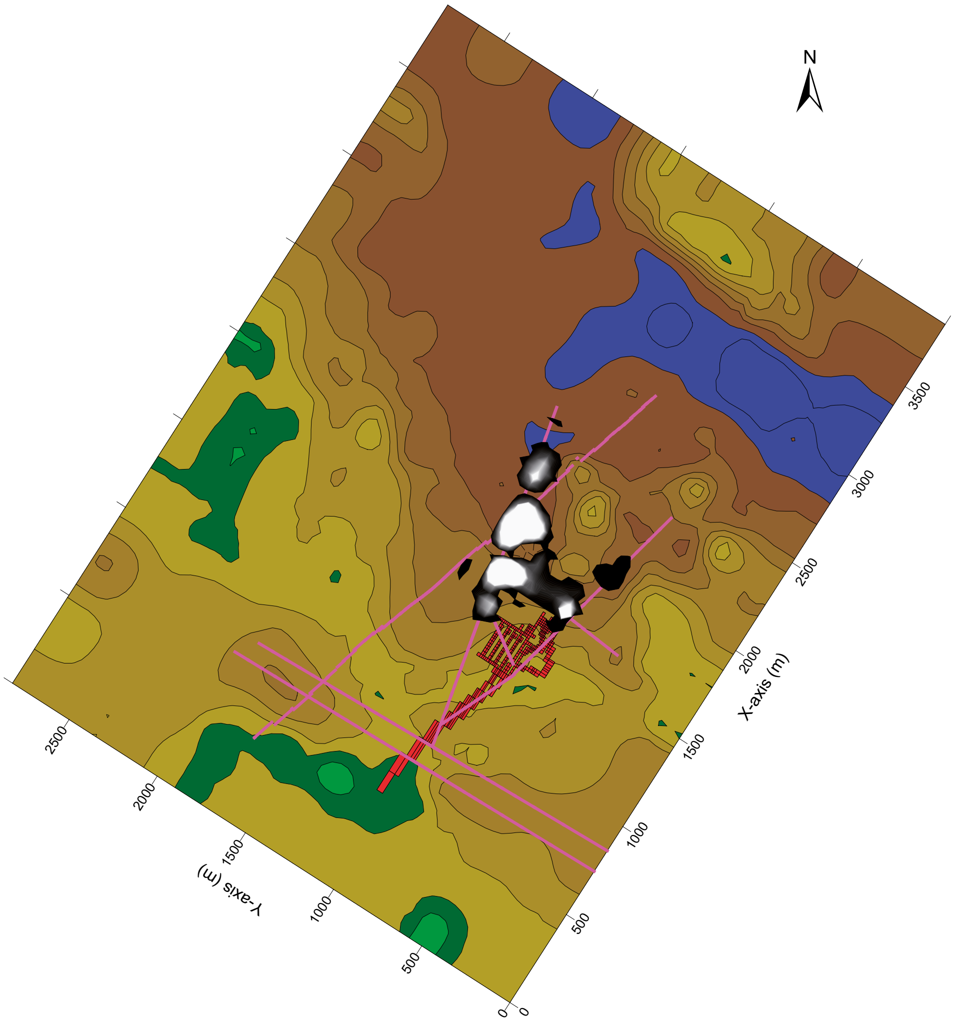


Figure 6-28. *Predicted discharge areas for the water flow from the silo repository and the rock vaults at 5,000 AD. The black-and-white areas represent discharge areas, red shows the repository and the access ramp and pink shows fracture zones (results of uncertainty analysis in /Holmén 2007/).*

Local wells at SFR 1

The effect that local wells can have on the groundwater's flow pattern in the environs of SFR 1 has been analyzed /Holmén and Stigsson 2001a/. The analysis was carried out by simulating wells and the influence of wells on the flow pattern in the local hydrogeological model.

Each well case included one well. The water withdrawal rate (well discharge) represents the requirement for a small farm. The wells were located upstream and downstream of the repository, in fracture zones or in the rock mass very near the tunnel system, but also directly into the repository. The studied well cases were simulated under steady-state conditions.

Well upstream of the repository

The results of the well simulations show that if a well is located upstream of the repository, the probability that it will be contaminated by radionuclides from SFR 1 is very small.

Well inside the repository

If a well is located inside the tunnel system, it is likely that it will eventually dominate the flow pattern inside the tunnel system, and most of the contaminated water in the tunnel system will flow towards the well. Owing to the extent of the tunnel system and the tunnel plugs, however, not all contaminated water will reach the well. A well inside the tunnel system will also give rise to an increased water flow through the silo repository and the rock vaults. Since the tunnel system has very high permeability/conductivity, it is probable that almost all water produced by the well will come from the tunnel system. If a well is located inside the silo repository or a rock vault, it is thus probable that all water produced by the well is contaminated and that there is no dilution with clean water in this case.

An abandoned and unsealed well, for example an old drinking water well or an investigation borehole, that is located in a tunnel will affect the water flow through the tunnel system. This is true even if no water is withdrawn from the well, since the well in such a case will constitute an effective transport pathway between the near-surface groundwater system and the water flow in the tunnel system. This case has been studied for BLA. A well that intersects BLA, is left open and is subsequently abandoned has been simulated in the model. Provided that the water level in the well is equal to the level of the ground surface, the well will give rise to an increased water flow through BLA. In comparison with the situation without a well, the water flow will increase between 3 times (3,000 AD) and 7 times (5,000 AD), due to the position of the shoreline. In order for these water flows through BLA to be sustained, a high inflow is required to the well. It is possible that such quantities of water are available during the spring and autumn floods, but not during the winter and summer. It is therefore likely that the groundwater flow through the intersected tunnel will vary greatly, being much lower in the winter and summer than in the spring and autumn.

Well downstream of the repository

If a well downstream of the repository is located in a flow path from the silo repository or the rock vaults or below a discharge area for the water flow from the silo repository and the rock vaults, it is possible that the well will intercept contaminated water from the repository even if the well withdrawal rate is very low. If the well withdrawal rate is high, it is probable that such a well will intercept a large portion of the water flow from the silo repository and the rock vaults. If the well is located outside the flow paths from the repository and outside the discharge areas, the well withdrawal rate must be very high to change the natural flow pattern and collect contaminated water from the silo repository and the rock vaults.

However, it is unlikely that a single well could be such a strong sink in the groundwater flow system that it could change the natural groundwater flow so decisively. This is due to the large potential groundwater recharge (runoff) in the present climate and the relatively low conductivity of the rock mass. For example, the simulated wells in the rock mass outside the fracture zones show that the conductivity of the rock is so low that a large well withdrawal rate is not possible, and without a large well withdrawal rate no great change occurs in the flow pattern. The wells in the fracture zones show that a well in a reasonably large fracture zone, with a well withdrawal rate equivalent to that of a small farm, is not such a strong sink (the well withdrawal rate is not sufficiently great) for the well to significantly alter the flow pattern in the fracture zone. This is due to the relatively high conductivity of the fracture zone and the large potential groundwater recharge. It should, however, be pointed out that if a well in rock or a fracture zone is located next to or near the undisturbed flow path for the contaminated water, it is highly probable that the well will collect contaminated water even at a low well withdrawal rate. Predicted flow paths from the silo repository to a local well are illustrated in Figure 6-29.

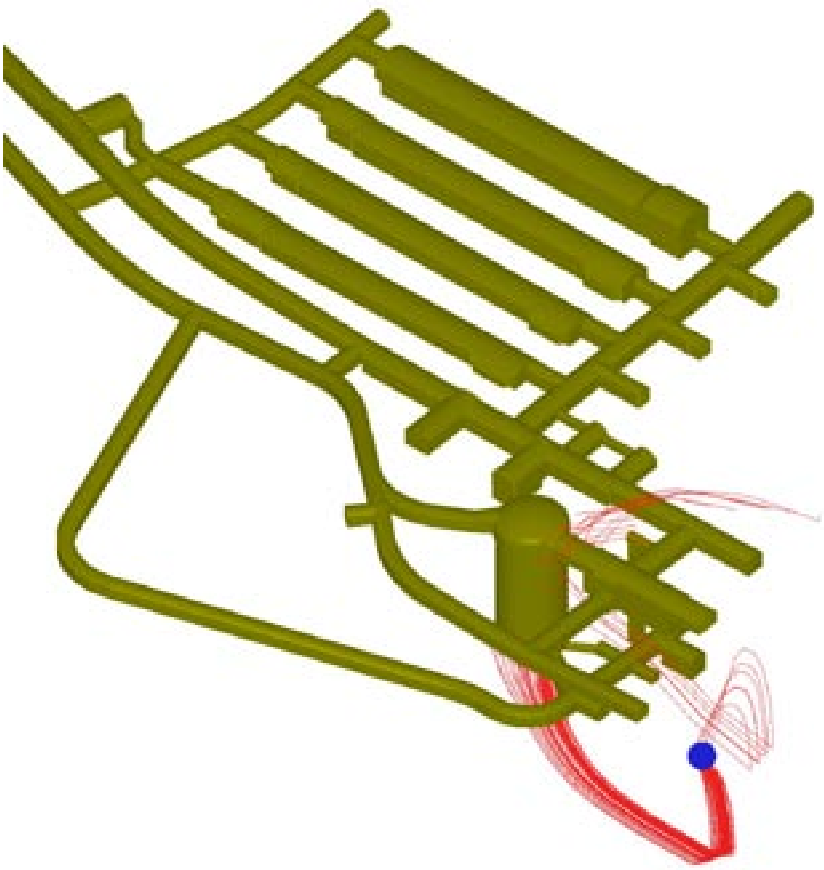


Figure 6-29. Example of predicted flow paths from the silo repository to a local well located in the intersection between zones 8 and 9 /Holmén and Stigsson 2001a/.

Dilution in wells

Dilution with clean water normally takes place in a well because the total well withdrawal rate is usually greater than the quantity of contaminated water reaching the well. An exception is if the well is located inside the silo repository or a rock vault. In this case it is likely that all of the discharged water will consist of contaminated water.

6.5.3 Mechanical evolution

The surrounding rock has good stability. Earthquakes can affect the stability of the rock as well as the stability of the repository. Since it is not possible to predict when future earthquakes will occur and what magnitude they will have, earthquakes are treated as a scenario. Background, statistics and impact of earthquakes are dealt with in the description of this scenario in Chapter 7.

The mechanical evolution of the repository is a combination of mechanical and chemical processes. The chemical evolution is described in section 6.5.4.

6.5.4 Chemical evolution

As has been observed for the preceding period, see section 6.4.4, the chemical evolution and the mechanical evolution of the repository are of importance for the durability of the engineered barriers and for the release of radionuclides and other species, particularly as regards sorption.

The point of departure for the chemical evolution during this period, 3,000 AD to 20,000 AD, is the evolution that has taken place during the first thousand years. The following description is thus a continuation of section 6.4.4. The background to the calculations and assessments described in the preceding section is not repeated in this section.

Among the external changes that have a bearing on the chemical evolution is the fact that the groundwater after about 1,000 years is expected to be fresh water /Holmén and Stigsson 2001a/.

Composition of the groundwater

Land uplift has proceeded so far that the groundwater flowing into the repository will be fresh (non-saline) throughout the period. A fresh groundwater could have a composition similar to that found today in wells in Östhammar Municipality, see Table 6-12 /Höglund 2001/.

Evolution of the barriers

Concrete and bentonite barriers

The reactions between the barrier materials and the groundwater have been modelled /Höglund et al. 2001, Gaucher et al. 2005, Cronstrand 2007/. The groundwater composition used in the geochemical calculations by /Höglund 2001/ and /Cronstrand 2007/ is the one shown in Table 6-12, whereas this composition was modified somewhat in the study by /Gaucher et al. 2005/, where the pH was increased to 7.7 and the potassium concentration was reduced to 2 mg/l. These modifications of the composition are within the interval for minimum and maximum values in Table 6-12. /Gaucher et al. 2005/ also added iron in a concentration of 2 mg/l.

One of the calculation cases in /Höglund 2001/ sheds light on the effects of a cracked concrete barrier, which is a possibility that cannot be ruled out for the BTF repositories during this period. It is assumed in the calculations that the groundwater flows through the concrete at a flow rate equivalent to one pore water exchange in about 15 years. The results show extensive mineral alteration. Up to 0.3–0.4 m into the concrete in the water's flow direction, the concrete is largely depleted of calcium silicate hydrates after 10,000 years. The depletion of calcium silicate hydrates affects the sorption capacity. As the leaching front moves in the flow direction, the porosity first declines from 10% to about 8%, after which it increases up to about 17% after 10,000 years. The increase is due to the fact that the calcium silicate hydrates are leached out and the new minerals that are formed take less space.

Table 6-12. Composition of future inflowing fresh groundwater, based on data from existing wells in Östhammar Municipality (ion concentrations in [mg/l]) /Höglund 2001/.

Parameter	Proposed value	Min. value *	Max. value *
Redox [mV]	Reducing	–100	–400
pH	7.49	6.7	8.7
SO_4^{2-}	50	3	110
Cl^-	45	5	1,000
Na^+	100	20	200
K^+ *	4	0.2	10
Ca^{2+}	35	25	140
Mg^{2+}	9	3	10
HCO_3^- (alk)	300	170	540
Si as SiO_2(aq)	5.9		
Electrical balance [%]	–0.08		

* These values are based on measurements in Swedish groundwater /SNV 1997, SNV/SGU 1995/.

Calculations of concrete degradation solely with diffusive transport, as can be expected in BMA /Höglund 2001, Cronstrand 2007/, show that the concrete is leached of portlandite and calcium silicate hydrates only in the outermost decimetre. The depletion of calcium silicate hydrates may entail a slightly higher diffusivity and poorer sorption capacity in the outermost decimetre of the concrete than in the rest of the concrete barriers. According to the calculations, a decrease in porosity takes place in the outermost concrete at the same time as it increases further into the concrete /Höglund 2001, Cronstrand 2007/.

The geochemical evolution of the silo repository under the assumption of diffusive transport has been calculated by /Gaucher et al. 2005/. Conditions in 12,000 AD are described below, see also Figure 6-30.

The concrete nearest the bentonite has weathered so that the outermost third has been leached of portlandite. Furthermore, the entire degradation sequence CSH_1.8, CSH_1.1 to CSH_0.8 (tobermorite) can be seen at the outer edge. These changes are not expected to lead to any important changes in the properties of the concrete barrier.

After 10,000 years, a third of the total quantity of montmorillonite in the bentonite has been dissolved and calcium silicate minerals, zeolites and new clays have been formed at the interfaces to the concrete silo and the shotcrete. The new minerals have somewhat different properties than the original montmorillonite, including poorer swelling properties and a higher molar volume /Gaucher et al. 2005/. These properties do not change so much as to cause convection in the bentonite barrier /Gaucher et al. 2005/. The possibility cannot be ruled out that the barriers will eventually lose some of their plastic properties, which could entail a higher risk of cracking and higher hydraulic conductivity. The changes in porosity and mineral composition that may be

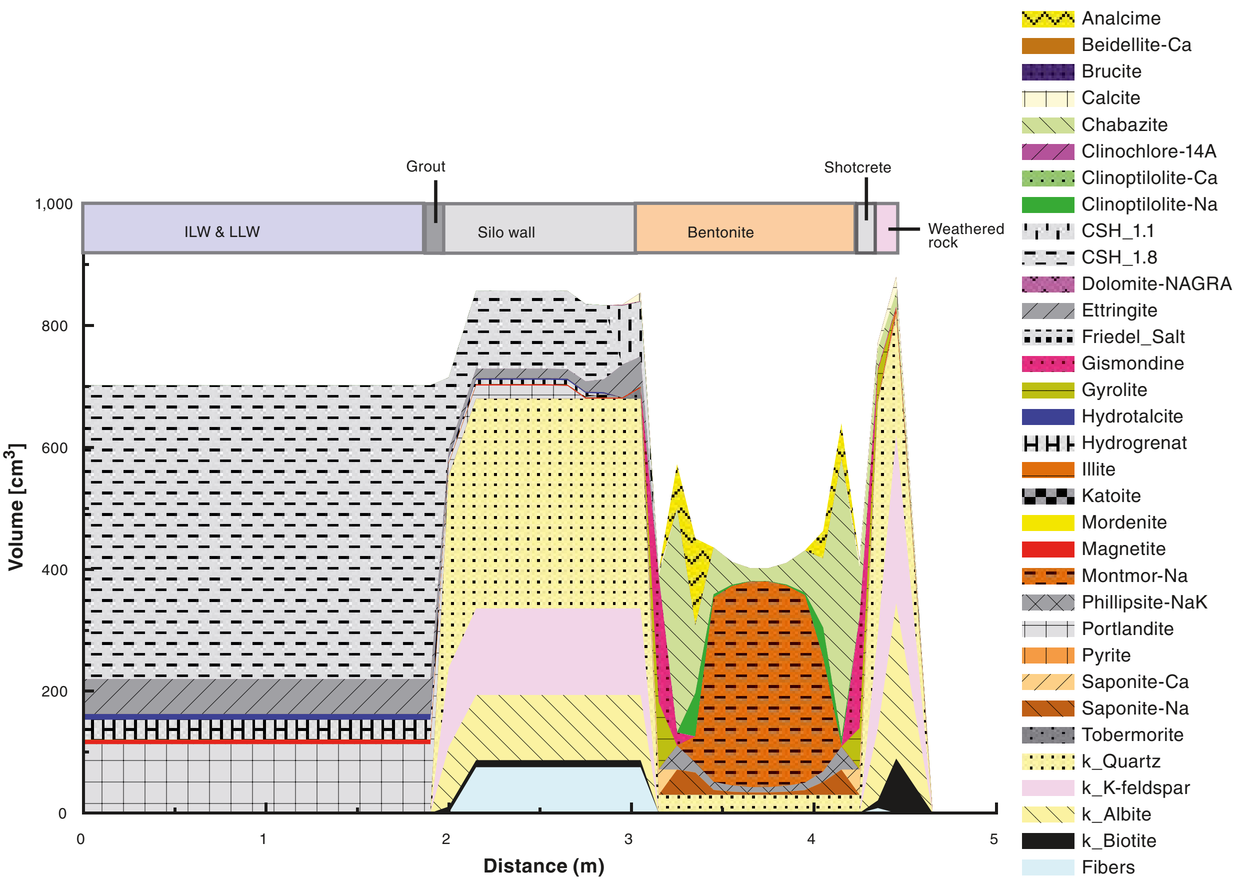


Figure 6-30. *Mineralogical composition in the system waste matrix – grout – silo wall – bentonite – shotcrete – rock after 10,000 years of leaching (simulation with normal pore diffusion, weathered rock and non-saline groundwater) /Gaucher et al. 2005/.*

caused by the alteration processes are not expected to lead to higher diffusion coefficients than for unaffected barriers. When it comes to sorption, the minerals that are probable formed, such as zeolites with generally high sorption of cations, should be as good or better sorbents than the original minerals. The values that are chosen for the unaffected bentonite barriers are therefore assumed to be representative of the whole period.

Based on the calculations that have been done regarding leaching of concrete, concrete moulds and cement matrices are not expected to be subjected to significant leaching of cement components during the period up until 12,000 AD (end of the study) /Höglund 2001/ and for the silo repository up until 100,000 AD /Gaucher et al. 2005/.

Water composition in the barriers

pH

The geochemical calculations, with diffusing groundwater, show that after 10,000 years the pH will have decreased slightly in the outermost parts of the concrete barriers, while the inner parts retain a pH buffered by leaching of portlandite, i.e. pH above 12 /Höglund et al. 2001, Gaucher et al. 2005, Cronstrand 2007/.

The results of a calculation where there is an exchange with groundwater flowing through the concrete show a much more rapid degradation of the concrete /Höglund 2001/. This calculation illustrates the effects of a cracked concrete barrier. In the outermost decimetre of the concrete the pH falls below 10 after only 5,000 years.

Based on this it can be concluded that the water in the concrete barriers in the silo repository, and in the interior of the concrete barriers in BMA, will retain a pH greater than 12 during the entire period. At the end of the period the pH in the outermost part of the concrete lid and the concrete walls in BMA may fall to 11, due to the dissolution of calcium silicate hydrate (CSH) phases. In the BTF repositories, cracking cannot be ruled out, and the degradation may be so extensive that the pH falls below 10. The water in the bentonite and sand/bentonite barriers in the silo repository and in the gravel backfill in the BMA and BTF repositories is expected to have a pH between that of the groundwater and that of the concrete pore water. In BLA the pH of the groundwater is expected to prevail throughout the period.

Redox conditions

Reducing conditions are assumed to prevail in all barriers and during the entire period in all repository parts (see also preceding period "Redox conditions"). Inflowing groundwater is expected to be reducing due to microbial processes at the surface and the fact that the oxygen that was present in the repository at closure was consumed during the preceding period. The presence of iron materials ensures a reducing environment. The time it takes for all iron material to corrode at a corrosion rate under anaerobic conditions of 1 µm/year has been calculated. The results show that it takes about 10,000 years for all material to corrode. The corrosion products of iron can also contribute to buffering the redox conditions. Microbial processes will degrade organic material in the waste, and these processes will also contribute to maintaining reducing conditions in the repository.

Ionic strength

In all repository parts except BLA, the water will have a high concentration of dissolved salts throughout the period owing to the concrete environment, despite the fact that the groundwater is expected to be non-saline. However, the surrounding rock will have low salinities due to the non-saline groundwater.

Complexing agents

It was noted in section 6.4.4 that ISA, which is formed by alkaline degradation of cellulose, could after only a thousand years reach concentrations that could entail some impact on the sorption of radionuclides. Alkaline degradation is expected to continue throughout this period, from 3,000 AD to 20,000 AD, as it is a very slow process.

The concentration of ISA inside waste packages has been calculated based on estimated quantities of cellulose materials in different waste types in SFR 1 /Fanger et al. 2001/. The results below are based on a degradation of approximately 10% of the quantity of cellulose during 10,000 years. The calculated concentrations show that several waste types can give rise to such high concentrations of ISA (greater than 10^{-4} M) inside the waste packages that the possibility of some impact on the sorption of tri- and tetravalent radionuclides there cannot be ruled out. In two of the waste types in BMA, the concentration of ISA is calculated to be so high (greater than 10^{-2} M) that the possibility of some impact on the sorption of divalent radionuclides as well cannot be ruled out. The possible impact of ISA on sorption at the calculated ISA concentrations is so small that it is covered by the conservative choice of Kd values made for cement/concrete /SKB 2001c/. These data are used in the deterministic calculations of radionuclide transport in the main scenario /Thomson et al. 2008a/.

Colloids

Section 6.4.4 described how the presence of colloids is inhibited by calcium ions. The concrete environment, which contributes to high calcium concentrations, and groundwater with calcium concentrations above 40 mg/l entail a negligible colloid concentration. During this period, 3,000 AD to 20,000 AD, the concrete environment is expected to be retained in the silo repository and the BMA and BTF repositories, so it can be assumed that they contain negligibly small quantities of colloids. The fresh (non-saline) groundwater has been assumed to have a calcium content according to Table 6-5 in the interval 25–140 mg/l, based on measurement data from existing wells in Östhammar Municipality. This suggests that the presence of colloids in the water in BLA should also be low.

6.5.5 Status of safety functions for the period from 3,000 AD to 20,000 AD

A number of safety functions and safety performance indicators have been defined for the safety assessment, see Chapter 5. Safety functions and safety performance indicators are tools for analyzing the future performance of the repository and for arriving at a complete set of scenarios. The safety functions defined for SFR 1 during the period in question are examined below to determine whether the safety function remains unchanged or whether it changes, and if so how. Uncertainties and deviations from the above-described status of the safety functions comprise one of the cornerstones of scenario selection in Chapter 7.

Low flow in repository parts

The safety function “low flow in repository parts” is judged with the aid of two performance indicators: fracture transmissivity and hydraulic gradient. It is noted in section 6.4.2 that the site for SFR 1 was selected in part because it is situated in an area with a limited hydraulic gradient and limited fracture transmissivity. The fracture transmissivity can be changed by chemical reactions in the fractures, but these changes are judged to be very slow during the period. Greater changes in fracture transmissivity can be expected in conjunction with earthquakes, which is dealt with in scenario selection, see Chapter 7. Continued shoreline displacement causes the hydraulic gradient to increase slightly during the period. By about 5,000 AD, shoreline displacement does not affect the hydraulic gradient any more, since the repository is located far from the shoreline and the gradient is controlled by the local topography. The change in the hydraulic gradient is reflected in the regional flow, which has been calculated to be 5 litres/m^2·year at 3,000 AD and 7 litres/m^2·year at 5,000 AD /Holmén and Stigsson 2006a/, see section 6.5.2. According to the reference evolution for the climate, based on the latest glacial cycle, a shallow permafrost will occur during the period, which entails a limitation of the flow where the water freezes. The safety function "low flow in repository parts" is only affected to a small extent during the period.

Limited advective transport in concrete and bentonite barriers

The safety function "limited advective transport" has been chosen for the hydraulic function of the engineered barriers. The safety function entails limited advective transport through the concrete in the BMA and BTF repositories and limited advective transport through the bentonite in the silo repository.

The concrete barriers

Three indicators have been chosen to assess how the safety function of the concrete barriers develops with time: hydraulic conductivity of concrete tanks in BTF, hydraulic conductivity of concrete walls in BMA and temperature in the concrete barriers.

Hydraulic conductivity of concrete tanks in BTF – A larger water flow through the concrete tanks is expected in the BTF repositories than through the concrete moulds in BMA, see Table 6-9. The higher water flow entails a more rapid degradation of the concrete and thereby an increased risk of cracking. During this period an extensive chemical degradation of the BTF tanks is expected, which entails a great change in their porosity and hydraulic conductivity, see section 6.5.4. According to the hydrogeological calculations, the water flow through the BTF repositories is expected to increase by approximately a factor of two compared with if the concrete had retained the same hydraulic conductivity as during the first 1,000 years, see section 6.5.2.

Hydraulic conductivity of concrete walls in BMA – According to the description in section 6.5.4 of the mechanical and chemical processes, they will somewhat affect porosity and fracture frequency, which affects the conductivity of the concrete. According to the data report for the SAFE project /SKB 2001c/, the value of the hydraulic conductivity, $8.3 \cdot 10^{-10}$ m/s, is representative for structural concrete with some small penetrating cracks. The chemical and mechanical evolution described above in section 6.5.4 is not expected to have such a great impact that this value is not representative for the whole period. This value has been used in the hydrogeological calculations that are presented in section 6.5.2.

Temperature – According to the description in section 6.4.1, the temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn controlled by prevailing climatic conditions. In the reference evolution's two variants of climate evolution and the analysis of how deep the permafrost reaches (see Figures 6-3 and 6-5),it is shown that the permafrost does not reach repository depth until 10000 AD. In a study of long-term stability as a consequence of freezing and thawing of the concrete /Emborg et al. 2007/, it is judged that the concrete will not freeze apart until the permafrost period that occurs in about 45,000 years and 90,000 years, respectively, in the two variants of climate evolution.

The safety function "limited advective transport" will be changed for the BTF repositories according to what has been described above for the performance indicator "hydraulic conductivity of concrete tanks". For the concrete structure in BMA, no changes of importance for the barrier's safety function are expected. It is not likely that the permafrost at around 10,000 AD will cause the concrete to freeze, but the margin is limited.

Bentonite barriers

Three indicators have been chosen to assess how the safety function of the concrete barrier develops over time: hydraulic conductivity of bentonite, temperature and gas pressure in the silo. The status of these safety performance indicators during the period is presented below.

Hydraulic conductivity of bentonite – The hydraulic conductivity of the bentonite is affected very slowly by the chemical reactions that occur, see the description in section 6.5.4. No other processes are expected to occur that have any significant impact on the hydraulic conductivity of the bentonite during the period. According to the data report for the SAFE project /SKB 2001c/, the value of the hydraulic conductivity of bentonite, $6 \cdot 10^{-12}$ m/s, is representative for intact barriers for 10,000 years. This value of the hydraulic conductivity means that transport through the bentonite barrier is controlled by diffusion. This value has been used in the hydrogeological calculations that are presented in section 6.5.2.

Temperature – According to the description in section 6.4.1, the temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn controlled by prevailing climatic conditions. In the reference evolution's two variants of climate evolution and the analysis of the temperature in the rock (see Figure 6-22), the temperature in the repository does not fall below –5°C during the period in question, which is the temperature required for the bentonite barriers to freeze.

Gas pressure in the silo – According to the description in section 6.4.4, only a small gas pressure is required for gas to be transported through concrete packages, porous concrete and the concrete structure. In order for the gas to find its way out through the gas evacuation pipes and the sand/bentonite barrier in the top, a gas pressure must be built up equivalent to the opening pressure of the sand/bentonite barrier, which is around 15 kPa. The chemical reactions that are expected during the period years are not expected to lead to such great changes in the opening pressure of the sand/bentonite barrier that the gas pressure will be higher than around 15 kPa.

The safety function "limited advective transport in the bentonite barrier" will be largely unchanged and transport through the bentonite is expected to be controlled by diffusion during the period.

Good sorption in concrete barriers

A review of the parameters important for sorption has been done in section 6.5.4 and is summarized below.

High pH – Degradation of the concrete is judged to proceed slowly, and a high pH will be maintained in the concrete barriers in the silo repository and BMA. As far as the BTF repositories are concerned, cracking and thereby faster chemical degradation cannot be ruled out. The degradation gradually causes the concrete material to lose its chemical properties and the pH declines.

Reducing conditions – Corrosion of iron and microbial processes will provide a reducing environment in the repository during this period.

Low concentrations of complexing agents – A limited initial quantity of complexing agents is ensured by SKB's and the regulatory authorities' inspections during the operating phase. In addition to the initial quantity of complexing agents, additional complexants will be produced by degradation of organic material. The amount of complexing agents predicted for the period (see section 6.5.4) is so low that sorption is not affected to a greater extent than is included in the uncertainties for the selected sorption data.

Available sorption surface area – The available sorption surface area will be large, even if the concrete degrades. The available sorption surface area is not expected to be limiting for sorption.

In the case of the silo repository and BMA, no great change of the safety performance indicators occurs, so good sorption in concrete barriers is expected during the period.

In the case of the BTF repositories, cracking of the concrete tanks cannot be ruled out, which leads to increased degradation and thereby impaired sorption properties compared with the first 1,000 years.

No wells

The safety function "no wells" has the performance indicator "location in relation to shoreline". Since the shoreline has passed the repository after about a thousand years after closure, it will be possible to drill wells during the period.

6.6 Evolution of the repository during the period from 20,000 AD to 100,000 AD

The period from 20,000 AD to around 100,000 AD is characterized by permafrost reaching down into the repository and glaciation. The description of the reference evolution for this period will be focused on describing what happens under these climatic conditions.

The radioactivity in the waste continues to decay so that at 100,000 AD it is less than 0.5% of the activity at closure. At the beginning of the period, in 20,000 AD, the activity consists mainly of Ni-59 and inorganic and organic C-14, but the activity of C-14 declines rapidly. At the end of the period Ni-59 still dominates and Tc-99 has the next-highest activity.

6.6.1 Thermal evolution

The thermal evolution of the repository is controlled by the temperature in the surrounding rock and groundwater, which is in turn controlled by the climate. During this period the temperature in the repository will be so low that the entire repository freezes. In the reference evolution for the climate based on the latest glacial cycle, the temperature in around 45,000 AD is so low (less than –5°C) that both concrete and bentonite freeze, see Figure 6-22.

6.6.2 Hydrogeological evolution

A generic simulation of groundwater flows at SFR 1 under different future climatic conditions has been carried out by /Vidstrand et al. 2007/. In the study, the climate evolution based on the latest glacial cycle has been simplified in the same way as in the main scenario for climate evolution (see Chapter 7). The simplification entails that short periods with changed climate have been neglected so that the evolution only contains distinct periods with different climatic conditions and transitions between them. Table 6-13 shows the calculated results in the form of how much the groundwater flow in the rock has changed compared with current conditions.

During a period of permafrost, the extent of the permafrost is initially sporadic, later becoming discontinuous and finally continuous, in other words a gradual spreading of the permafrost cover. This results in changed groundwater flows. When the climate gets colder the permafrost extends over larger areas and also reaches greater depths. When permafrost reaches the repository, the water flow in the repository will be reduced sharply or even cease altogether, due to the fact that the permafrost greatly reduces the hydraulic conductivity of the rock, see Table 6-13.

In the reference evolution, the permafrost period is followed by the first period with glacial conditions, when an ice sheet covers the site. The subglacial permafrost, which initially occurs beneath the ice sheet, then acts as a hydrological barrier to the water flow. This period is therefore characterized by the fact that there is no groundwater recharge.

After the initial period of frozen, cold-based glacial conditions, groundwater recharge is reinstated, due to the fact that the proportion of permafrost in the ground has decreased and to basal melting in the warm-based ice sheet, see Figure 6-3. In local areas where groundwater discharge previously occurred under non-glacial conditions, the direction of the groundwater flow is reversed. This results in a predominant subglacial groundwater flow directed downward beneath the warm-based ice sheet, so that groundwater recharge occurs.

Table 6-13. Scaling factors for the groundwater flow in the rock in the reference evolution. Negative values indicate a change in the flow direction. The value 0.0001 shows that there is no groundwater flow and applies to areas where the rock is frozen. The value 0.01 shows that there are very low groundwater flows beneath the sea. Two calculation cases are presented: one where SFR 1 is located in a recharge area and one where SFR 1 is located in a discharge area /Vidstrand et al. 2007/.

Climate domain	Time (thousands of years)	Scaling factor Recharge area	Discharge area
Temperate	2–10	1	1
Sporadic/shallow permafrost	10–12	0.0001 (0.5 *)	0.0001 (0.2 *)
Temperate	12–25	1	1
Continuous/deep permafrost	25–57	0.0001 (10 *)	0.0001 (5 *)
Ice sheet advance	58	–10	150
Ice sheet	58–68	0.5	–0.5
Ice sheet retreat	68	–10	150
Submerged	68–77	0.01	0.01
Continuous/deep permafrost	77–93	0.0001 (10 *)	0.0001 (5 *)
Ice sheet advance	93	–10	150
Ice sheet	93–111	0.2	–0.2

* Groundwater flow in areas with talik

After the first glacial period is over, the area above SFR 1 is covered by water for about 9,000 years. When the area is then located above sea level, the climate is generally colder, occasioning new long periods of deep permafrost with reduced hydraulic conductivity in the uppermost 100 m or so of the rock.

During the second period of glaciation, which is also the most severe and starts after about 90,000 years, the ice sheet is initially cold-based during a much shorter time compared with what it was during the first glacial period, see Figure 6-3. As a result, water from basal melting of the ice sheet is available for groundwater recharge during most of this glacial period.

During glacial periods when the front of the ice sheet is located relatively close to the repository, groundwater recharge can also take place due to the fact that meltwater from the surface of the ice sheet reaches down to the ground beneath the ice, which can also contribute to groundwater recharge in cases where the extent of the permafrost permits.

After the second glacial period the area above SFR 1 is under water for about 10,000 to 12,000 years after the ice sheet has melted, see Figure 6-3.

The water flow in the silo repository and the rock vaults is also affected by the climate changes. The calculated scaling factors for the groundwater flow in the rock reported in Table 6-13 can be used to approximately estimate the changes in the water flow in the silo repository and the rock vaults. An approximate estimate of how much the water flow increases through the silo repository and the rock vaults as a result of degradation of the barriers can be obtained by comparing calculations performed for intact barriers with ones for degraded barriers /Holmén and Stigsson 2001a/.This comparison has been utilized in the radionuclide transport calculations, see section 8.4.1.

6.6.3 Mechanical evolution

The surrounding rock and the stability of the repository are affected by earthquakes. During this period the probability of earthquakes increases as a result of pressure changes both during and after the glacial period. As a result, the function of both the rock and the repository as barriers cannot be maintained with certainty during this period.

The impact of freezing and thawing on the stability of concrete and bentonite has been studied by /Emborg et al. m 2007/. The study was concentrated on the silo repository. The concrete used to build BMA is of the same quality as in the silo repository, which means the results can also be applied to the structures in BMA.

The concrete used in the silo repository and BMA is a construction concrete with a relatively low cement content, which means that the risk of early temperature cracks is low. Formally the concrete cannot be considered frost-resistant, since air entraining agents have not been added /Emborg et al. 2007/.

According to the climate evolution based on the latest glacial cycle, the temperature falls below –5°C in the repository for the first time in 45,000 AD. The pores in the concrete are then completely filled with water. The time required to water-saturate the pores in the concrete has been calculated to be up to 2,000 years /Emborg et al. 2007/. This means that the concrete is subjected to internal freezing /Emborg et al. 2007/. This internal freezing causes penetrating macrocracks that loosen up the concrete. Loosening of this kind is causes such a serious structural deterioration of the concrete that it cannot be relied on to remain intact after freezing and thawing. The material is broken up to such a degree that its function as a diffusion barrier is lost, but it still functions as a sorption barrier and, to a limited extent, as an advective barrier.

The bentonite will also have water-filled pores in 45,000 AD. The time for complete water saturation of the bentonite can be estimated from the work done within the framework of SR-Can /SKB 2006f/. Depending on many different factors, including type of bentonite, density of bentonite, mixing ratio between sand and bentonite, fracture content of surrounding rock etc, the time to water saturation of bentonite varies from a few years to around 500 years. In SFR 1, the time to complete water saturation of the surrounding bentonite is therefore likely to be on the order of 100 years. After freezing and thawing, the bentonite will retain its swelling properties and will act as a diffusion barrier during the periods when the area is not frozen /Emborg et al. 2007/.

The bentonite in the vertical gap between the concrete silo and the rock will exhibit ice lens formation /Emborg et al. 2007/. Ice lens formation entails that water is sucked into the freezing bentonite, where it accumulates in ice layers that gradually grow in thickness. The ice layers normally grow in a direction parallel to the heat flow. In this case, where the frost front is horizontal, the ice layers will grow in thickness vertically. The driving force for this process comes from the unfrozen water, which has a potential that is lower than that in the surrounding free water. This lower potential is a consequence of the fact that the water does not freeze at 0°C but at a lower temperature. The phenomenon is common in natural soil layers and is then termed frost heave. Ice lens formation can cause fractures to open in the surrounding rock. Swelling bentonite is then squeezed out into the fractures as it thaws. This can lead to some material loss and reduced density in the bentonite. The duration of the permafrost will not be of any importance for the heaves caused by ice lens formation. What is decisive for the size of the heaves is the time it takes for the frost front to pass the repository.

The sand/bentonite mixture that lies beneath and above the concrete silo is not affected by freezing and thawing as far as compression and hydraulic conductivity are concerned. These functions are not affected by the freeze-thaw cycle. The sand/bentonite mixture will not exhibit ice lens formation because the clay content is too low /Emborg et al. 2007/.

In the presence of an ice sheet there is a great risk for erosion of the bentonite. There are two possible types of erosion. The first is mechanical erosion, whereby the flow of water tears away particles from the bentonite. The other is erosion caused by dissolution of clay particles in the groundwater. The clay particles do not dissolve in the groundwater when the concentration of calcium ions is sufficiently high /SKB 2006a/. The concentration of calcium ions in the groundwater is expected to be sufficiently high under temperate conditions as well as under permafrost conditions. During ice ages, however, the concentration of calcium ions may be low, and in combination with a sharply elevated groundwater flow, erosion of the bentonite cannot be ruled out.

6.6.4 Chemical evolution

The chemical evolution is strongly affected by the different climate domains: temperate climate, permafrost and glaciation. A description of how permafrost and glaciation affect the composition of the water is given below. This is followed by a description of how the concrete and bentonite barriers are affected. Degradation of cellulose leads to continued production of the complexant ISA, which is also described below. It should be pointed out that during the time the water in SFR 1 is frozen, all chemical processes (including radionuclide transport) proceed very slowly.

Composition of the groundwater

Permafrost – effect on salinity

Under permafrost conditions, no great changes are expected in the salinity of the groundwater; a non-saline groundwater is expected. Salt exclusion due to freezing could increase the salinity of the groundwater /Vidstrand et al. 2007/, but the groundwater is not particularly saline before the onset of permafrost and the salts that are formed are moved to the bottom of the permafrost. Thus, the deeper the permafrost, the greater salt exclusion can be. Since SFR 1 is located at such a shallow depth and the salinity of the groundwater is low before the onset of permafrost, the effect of salt exclusion is negligible.

Glaciation – effect on salinity

When the repository is located beneath a warm-based ice sheet, the inflowing meltwater will result in low salinity in the repository. The weight of the ice cap beneath a glaciation depresses the repository below sea level, see Figure 6-3. When the ice sheet has retreated, the groundwater may become saline, like it is today. The subsequent shoreline displacement then leads once again to a less saline groundwater under temperate or permafrost conditions, see Figure 6-31.

Evolution of the barriers

Concrete and bentonite barriers

Degradation of the concrete and bentonite barriers continues in accordance with what has been described earlier in sections 6.4.4 and 6.5.4.

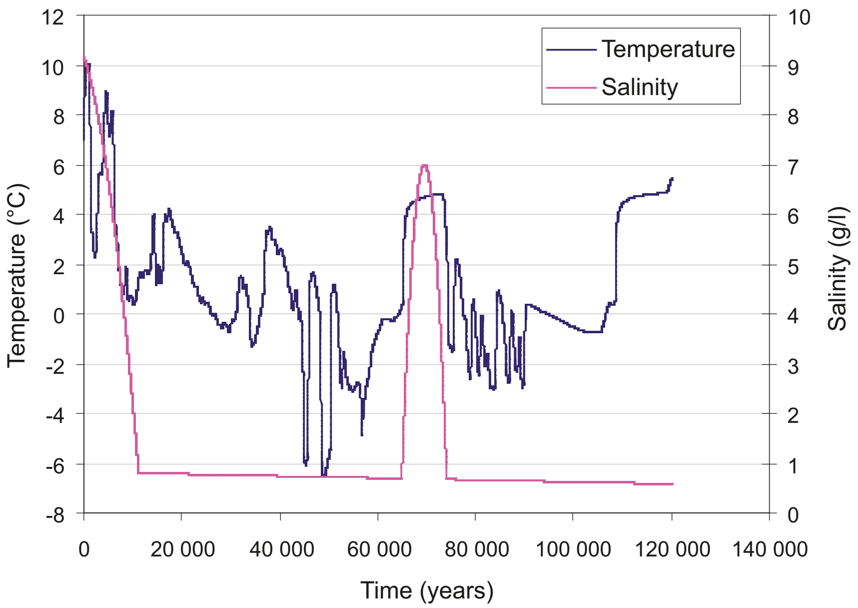


Figure 6-31. *Salinity variation in SFR 1 /Cronstrand 2007/.*

The geochemical calculations show that quite a few changes have occurred in both the concrete and the bentonite barrier in the silo repository after 100,000 years, see Figure 6-32 /Gaucher et al. 2005/. The montmorillonite, the clay mineral that gives the bentonite its shrinking and swelling capacity, is gradually transformed on contact with water with a high pH. After 100,000 years, only a small portion of the montmorillonite remains, see Figure 6-32. The possibility cannot be ruled out that the scope of the transformation is so great that the bentonite barrier loses its swelling capacity during this period. The calculations that have been carried out /Cronstrand 2007/ show a slower degradation of the montmorillonite.

Calculations /Gaucher et al. 2005, Cronstrand 2007/ show that portlandite (calcium hydroxide) has been leached completely out of the silo wall and the calcium silicate hydrates have been transformed after 100,000 years, see Figure 6-32.Only the first step in the transformation has occurred in the innermost part of the silo wall, i.e. portlandite has been leached out but CSH_1.8 remains. In the middle a second step in the transformation has occurred (CSH_1.1 has replaced CSH_1.8), and outermost the third step in the transformation has also occurred (CSH_0.8, also called tobermorite, has replaced CSH_1.1) /Gaucher et al. 2005/. As long as the leaching has not gone further than to these calcium silicate hydrates, the silo wall can be regarded as a concrete material as far as material and sorption properties are concerned.

As regards BMA, /Cronstrand 2007/ shows that the concrete wall has not been leached further than to calcium silicate hydrates. Since transport in the modelling only includes diffusion from the outer wall, it is likely that degradation will take place faster than calculated by /Cronstrand 2007/ owing to the fact that the concrete cracks on freezing and thereby allows advective transport.

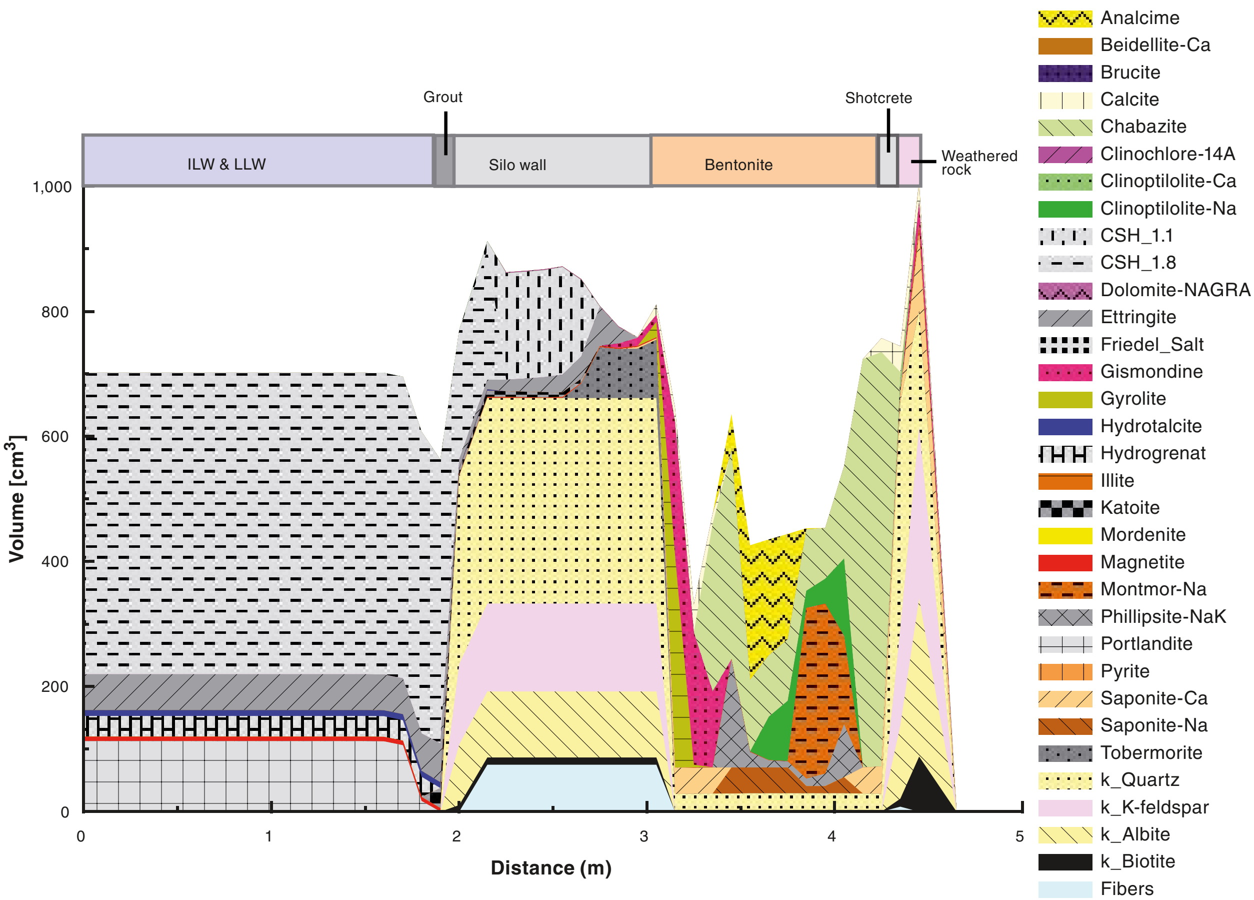


Figure 6-32. *Mineralogical composition in the system waste matrix – grout – silo wall – bentonite – shotcrete – rock after 100,000 years of leaching (simulation with normal pore diffusion, weathered rock and non-saline groundwater) /Gaucher et al. 2005/.*

Water composition in the barriers

Permafrost – effect on pH

The pH is controlled by fast chemical reactions, and permafrost is not expected to have any appreciable impact. The geochemical modelling shows that the pH in the concrete barriers will be above 11 after 100,000 years in the silo repository /Gaucher et al. 2005/ and BMA /Cronstrand 2007/. Freezing of the concrete barrier during permafrost causes cracking of the concrete, see section 6.6.3. In the case of BMA, which is not surrounded by a watertight bentonite, the probable result is that transport will be controlled by the water flow. Since transport in the geochemical modellings only includes diffusion from the outer wall, it is likely that degradation, and thereby pH reduction, will take place faster than calculated by /Cronstrand 2007/.

Permafrost – effect on redox conditions

During permafrost, and above all during melting of permafrost, oxygen-rich water will infiltrate through soil and rock. Even though microbial processes at the surface can be weakened by the cold, geochemical processes, such as degradation of illite and weathering of iron and sulphide minerals, will consume oxygen. These geochemical processes are expected to lead to general anoxic conditions in the water in the repository, but it is not certain that the buffer capacity is sufficient to give strongly reducing conditions.

The perennial freezing of rock volumes effectively shuts of the hydraulic circulation in the rock, at least locally /Vidstrand et al. 2007/. In this way, microbial populations can be isolated from the surface and methane can also be trapped. Microorganisms in the shallow rock can survive a permafrost and become active again after thawing. This means that reducing conditions can be expected, unless the supply of nutrients becomes a limiting factor. If methane is trapped in the rock, it will serve as a source of nutrients for the microbial population in the rock, see further in SR-Can's process report for the geosphere /SKB 2006g/.

In summary, it can be concluded that the redox conditions in the groundwater at repository level can be expected to remain reducing during permafrost and melting of permafrost, owing to a combination of microbial and geochemical reactions and processes. However, the possibility cannot be ruled out that there will be oxidizing conditions in the relatively near-surface location of SFR 1.

Glaciation – effect on pH

See above under the heading "Permafrost – effect on pH".

Glaciation – effect on redox conditions

When the ice sheet advances, great changes are induced in the groundwater flow conditions compared with the conditions that exist today, see section 6.6.2 /Jacquet and Siegel 2006/. Short periods of up-coning of deep reducing groundwater are followed by longer periods when glacial meltwater seeps down into the rock. After some time nearly all water around the repository will originate from meltwater. Compaction of snow to ice entails the entrainment of considerable quantities of air /Martinerie et al. 1992/. Glacial meltwater may therefore initially contain dissolved carbon dioxide and oxygen in higher concentrations than aerated water.

Dissolution of rock minerals, mainly iron(II) minerals, consumes oxygen. It is, however, possible that the expected high inflow of meltwater, when the edge of the ice sheet is near the repository, lasts for such a long time that the buffering capacity is not sufficient. This could result in oxygen reaching down to the repository.

As in the case of permafrost (see above), there is a possibility that microorganisms can survive glaciation. Microorganisms consume oxygen, but the uncertainties are great and the possibility that oxygen will reach down to the repository cannot be ruled out.

Complexing agents

The presence, formation and importance of different complexing agents was discussed in section 6.4.4. It was concluded there that degradation of cellulose in an alkaline environment can lead to the formation of isosaccharinic acid (ISA). ISA is a complexing agent which at high concentrations can affect the sorption of radionuclides, particularly tri- and tetravalent radionuclides.

According to /Fanger et al. 2001/, complete degradation of cellulose can take more than 100,000 years. This means that the risk of high concentrations of ISA increases with time and that the effect of cellulose degradation cannot be disregarded during this period.

6.6.5 Status of safety functions for the period from 20,000 AD to around 100,000 AD

A number of safety functions and safety performance indicators have been defined for the safety assessment, see Chapter 5. Safety functions and safety performance indicators are tools for analyzing the future performance of the repository and for arriving at a complete set of scenarios. The safety functions defined for SFR 1 during the period in question are examined below to determine whether the safety function remains unchanged or whether it changes, and if so how. Uncertainties and deviations from the above-described status of the safety functions comprise one of the cornerstones of scenario selection in Chapter 7. It should, however, be noted here that SFR 1 is not designed to function for such a long period of time as 100,000 years.

Low flow in repository parts

The safety function "low flow in repository parts" is judged with the aid of two performance indicators: fracture transmissivity and hydraulic gradient. Fracture transmissivity can change as a consequence of earthquakes. The probability of earthquakes increases as a result of pressure changes both during and after the glacial period. Earthquakes are dealt with in scenario selection, see Chapter 7. Minor changes in the hydraulic gradient occur as a consequence of shoreline displacement. The hydraulic gradient is greatly altered as the ice sheet advances and retreats. The change in the hydraulic gradient is reflected in the regional flow, which has been calculated to increase about 100 times when an ice sheet advances or retreats, see section 6.6.2.

Limited advective transport in concrete and bentonite barriers

The safety function "limited advective transport" has been chosen for the hydraulic function of the engineered barriers. The safety function entails limited advective transport through the concrete in the BMA and BTF repositories and limited advective transport through the bentonite in the silo repository.

The concrete barriers

Three indicators have been chosen to assess how the safety function of the concrete barriers develops with time: hydraulic conductivity of concrete tanks in BTF, hydraulic conductivity of concrete walls in BMA and temperature in the concrete barriers.

Hydraulic conductivity of concrete tanks in BTF – A sharp deterioration in the hydraulic conductivity in the concrete tanks was expected already during the preceding period. The continued degradation is not expected to further affect this hydraulic conductivity.

Hydraulic conductivity of concrete walls in BMA –A sharp deterioration in the hydraulic conductivity occurs due to the fact that the concrete cracks when it freezes and thaws during the permafrost domain, which reaches down to repository depth during this period, see section 6.6.3.

Temperature in the concrete – According to the description in section 6.4.1, the temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn controlled by prevailing climatic conditions. According to the reference evolution for the climate based on the latest glacial cycle and analysis of how the climate affects the temperature in the rock (see Figure 6-22), the temperature falls below 0°C, which is the criterion for freezing of the barriers in the repository. For the other alternative to the reference evolution for the climate with increased greenhouse effect as well, the temperature falls below 0°C during the period, although this takes place later.

During this period there is a large increase in advective transport in the concrete, except when the water is frozen.

The bentonite barrier

Three indicators have been chosen to assess how the safety function of the concrete barrier develops over time: hydraulic conductivity of bentonite, temperature and gas pressure in the silo. The status of these indicators during the period is presented below.

Hydraulic conductivity of bentonite – According to the description in 6.6.3, the bentonite regains its hydraulic properties after freezing, because its swelling capacity has a self-healing effect. However, due to the degradation of the bentonite to minerals that lack swelling capacity in combination with freezing, there is a risk that its hydraulic conductivity will increase. The concentration of calcium ions may be low during ice ages, and in combination with a sharply elevated groundwater flow, erosion of the bentonite cannot be ruled out, resulting in great changes in its hydraulic conductivity.

Temperature – According to the description in section 6.4.1, the temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn controlled by prevailing climatic conditions. According to the reference evolution for the climate based on the latest glacial cycle and analysis of how the climate affects the temperature in the rock (see Figure 6-22), the temperature falls so low, below –5°C, that the bentonite freezes. For the other alternative to the reference evolution for the climate with increased greenhouse effect as well, the temperature falls so that the bentonite freezes.

Gas pressure in silo – No assessment is needed of this safety performance indicator, since such great changes in the other two indicators are expected.

In summary, the possibility cannot be excluded that a large increase will occur in advective transport through the bentonite barrier during this period.

Good sorption in concrete barriers

A review of the parameters important for sorption has been done in section 6.5.4 and is summarized below.

High pH – The concrete in SFR 1 degrades slowly during the period in question, even taking into consideration the evolution of the climate according to /Cronstrand 2007/, and the pH decreases to around 11. Cracking as a result of freezing of the concrete can lead to faster leaching of the concrete. This leads to poorer sorption, particularly in BTF, but also in BMA and possibly also in the silo repository during the period.

Reducing conditions – When the ice sheet retreats, large quantities of oxygenated water will be able to enter the repository. Reducing conditions will therefore not prevail with certainty during the whole period in SFR 1, which is located at a relatively shallow depth. Nor is it completely certain that reducing conditions will prevail in the repository in conjunction with permafrost.

Low concentrations of complexing agents – Since degradation of cellulose is a very slow process, it can proceed throughout the period. This means there is a risk that the concentrations of the complexant isosaccharinic acid, which is formed by alkaline degradation of cellulose, can be so high that sorption of radionuclides is affected negatively.

Available sorption surface area – As previously observed (see section 6.5.5), the available sorption surface area is not expected to be affected so much, even if the concrete degrades. The available sorption surface area is judged to be sufficient so that sorption is not limited.

Sorption is affected negatively during this period. A gradual deterioration takes place, but above all it can be observed that when the concrete in BMA freezes apart during deep permafrost and when the integrity of the bentonite barrier can no longer be guaranteed during an ice age, a great deterioration occurs in the sorption properties.

No wells

The safety function "no wells" has the performance indicator "location in relation to shoreline". Wells will be able to be drilled during part of this period, since the repository will alternate between lying beneath the land and beneath the sea, see Figure 6-3.

6.7 Summary of the status of the safety functions

A number of safety functions and safety performance indicators have been defined for the safety assessment, see Chapter 5. Safety functions and indicators are tools for analyzing the future performance of a repository and for arriving at an comprehensive set of scenarios. Figure 6-33 presents an overall assessment of the status of the safety functions for the reference evolution. The reasons for the assessment of the different periods have been presented in sections 6.4.5, 6.5.5 and 6.6.5.

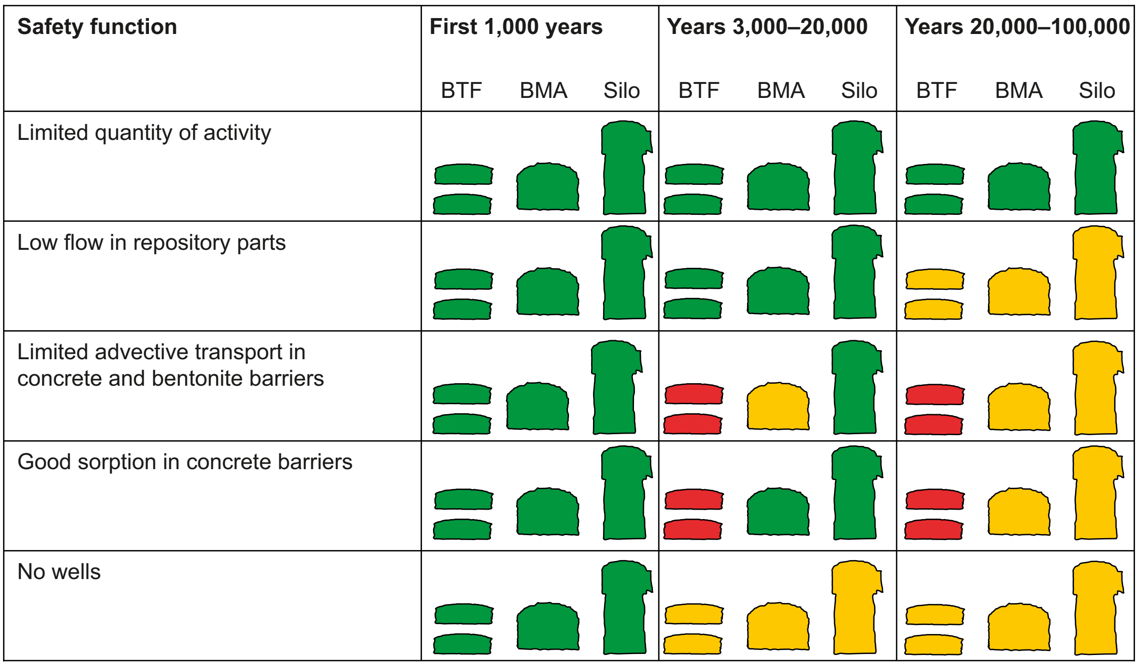


***Figure 6-33.** Reference evolution – assessment of the safety functions. Green = the safety function changes insignificantly, Yellow = the safety function deteriorates considerably at some time during the period, Red = the safety function is not maintained during the period.*

7 Selection of scenarios

7.1 Introduction

The reference evolution in Chapter 6 describes a reasonable evolution of SFR 1 based on knowledge of the processes that are assumed to be of importance for the long-term safety of the repository. However, it is impossible to assert that the evolution described is the only possible one, or that uncertainties in the input data that control the processes are fully known. Alternative repository evolutions are therefore posited in this chapter to shed light on the effect of these uncertainties. Scenarios are arrived at by identifying events, processes and data uncertainties[1] that cause the future evolution to differ from the reference evolution.

This chapter starts, in section 7.2 below, by presenting the regulatory requirements on scenario descriptions as they are set forth in SKIFS 2002:1 and SSI FS 1998:1, with associated guidelines in SSI FS 2005:5. The method that is used to select scenarios based on the given requirements is presented in section 7.3, and the selected scenarios are presented in subsequent sections. The radiological consequences of the different scenarios are explored in subsequent chapters: Chapter 8 describes the selected calculation cases, Chapter 9 presents dose results, and Chapter 10 presents a risk evaluation of the selected scenarios based on scenario probabilities described here (Chapter 7) and results from radionuclide transport calculations.

7.2 Regulatory requirements

The following three types of scenarios are defined in the guidelines to SKIFS 2002:1:

The main scenario *should be based on the probable evolution of external conditions and realistic or, where justified, pessimistic assumptions with respect to the internal conditions. It should comprise future external events that have a significant probability of occurrence or that cannot be shown to have a low probability of occurrence during the time covered by the safety assessment. Furthermore, it should be based as far as possible on credible assumptions with respect to internal conditions, including substantiated assumptions concerning the occurrence of manufacturing defects and other imperfections, which allow for an analysis of the repository's barrier functions (it is, for example, not sufficient to always assume that the waste containers remain leaktight for a long time, even if this can be shown to be the most probable case). The main scenario should be used as the starting point for an analysis of the impact of uncertainties (see below), which means that the analysis of the main scenario also includes a number of calculation cases.*

Less probable scenarios *should be prepared for evaluation of scenario uncertainty (see also below). These include variants of the main scenario with alternative sequences of events as well as scenarios that take into account the impact of future human activities such as damage inflicted on barriers. (Injuries to humans intruding into the repository are covered by residual scenarios, see below). Analysis of less probable scenarios should include analysis of uncertainties that are not evaluated within the framework of the main scenario.*

Residual scenarios *should include sequences of events and conditions that are selected and studied independently of probabilities in order to shed light on the importance of individual barriers and barrier functions. The residual scenarios should also include cases to shed light on injuries to humans intruding into the repository as well as cases to shed light on the consequences of an unclosed repository that has been left unmonitored.*

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[1] Compared with the features, events and processes of the FEP analysis, data are used in part to describe features, but also to quantify events or processes in a way necessary for further analysis.

Regarding probabilities it is said that

The probabilities *that scenarios and calculation cases will actually occur should be estimated as far as possible to permit risk calculation.*

SSI FS 1998:1 and the guidelines SSI FS 2005:5 state the following:

The assessment of the protective capability and environmental consequences of the repository should be based on a set of scenarios that together illustrate the most important sequences of events for the evolution of the properties of the repository, its environs and the biosphere.

In view of the great uncertainties associated with the assumptions regarding climate evolution in a remote future and in order to facilitate the interpretation of the risk to be calculated, the risk analysis should be simplified to include several possible climate evolutions.

A realistic set of biosphere conditions should be associated with each climate evolution. The different climate evolutions should be selected so that they together illustrate the most important and reasonably foreseeable sequences of future climate domains and their impact on the protective capability and environmental consequences of the repository.

The risk from the repository should be calculated for each assumed climate evolution by weighing together the risk contributions from a number of scenarios that together illustrate how the more or less probable sequences of events in the repository and the surrounding rock affect the repository's protective capability and environmental consequences. The calculated risk should be reported and evaluated separately for each climate evolution in relation to the regulations' criterion for individual risk. It should thus be possible to show that the final repository complies with the risk criterion for the alternative climate evolutions. If a lower probability than one (1) is given for a particular climate evolution, this should be backed up by, for example, expert statements.

With regard to human impact, the guidelines state the following:

A number of scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository and some examples of other activities that indirectly lead to a deterioration in the protective capability of the repository, for example by changing the hydrological or hydrogeochemical conditions in the repository or its environs. The selection of intrusion scenarios should be based on present-day living habits and technology and take into consideration the properties of the repository. The consequences of the repository's disturbed protective capability should be illustrated by calculations of the doses for individuals in the most exposed group, and reported separately and independently of the risk analysis for the undisturbed repository. The results should be used to shed light on conceivable countermeasures and to provide a basis for the application of best available technology.

SSI's guidelines SSI FS 2005:5 also mention "*Special scenarios*":

For repositories primarily based on containment of the spent nuclear fuel or nuclear waste, an analysis of a conceivable loss of one or more barrier functions of key importance for the repository's protective capability during the first thousand years after closure should be made separately and independently of the risk analysis. The purpose of such an analysis should be to clarify how the different barriers contribute to the protective capability of the final repository.

7.3 Method for scenario selection

The reference evolution presented in Chapter 6 describes a reasonable evolution of the repository's environs and is based on realistic or conservative assumptions regarding the internal evolution of the repository. The reference evolution is the basis for the main scenario presented in section 7.4.

Less probable scenarios and residual scenarios are constructed based on alternative repository evolutions. The alternative repository evolutions are identified by investigating which events, processes and data uncertainties can lead to a situation where the safety functions presented in Table 7-1 cannot be maintained[2]. The alternative repository evolutions are initially regarded as hypothetical and therefore not necessarily associated with any process or event, but are arrived at by positing that the safety function cannot be maintained. For each alternative repository evolution, an analysis is then made of whether there is a reasonable possibility (a scenario-generating event, process or data uncertainty) that the alternative repository development could occur. If this is the case, a scenario is defined based on the alternative evolution and the scenario-generating uncertainty.

Sections 7.5.1–7.5.5 present for each safety function alternative repository evolutions and the uncertainties in events, processes or data that could lead to the occurrence of the alternative repository evolution. The repository and geosphere interaction matrices that illustrate the function of the repository are used for this, see further Chapter 3.

In the interaction matrices, the state of the system (for example stress state or groundwater composition) is represented by the diagonal elements, while off-diagonal elements represent processes and interactions between the different diagonal elements (for example how the groundwater composition is affected by the hydrological conditions in the repository). In the interaction matrices, all off-diagonal elements have been given a priority that reflects the importance of the interaction. For each safety function, the following is presented in sections 7.5.1–7.5.5:

1. An introductory text where the safety function is described, along with how the safety function is represented in the interaction matrices. This initial identification serves as a basis for further analysis where consequences and scenario-generating processes, events and data uncertainties are identified.
2. The interactions judged to be important for each safety performance indicator are presented under the heading "Identified interactions of importance for the safety function". Important interactions are in this case those that have priority 2 or 3 (are red or yellow) in the interaction matrix. If interactions to other diagonal elements are found, interactions to the diagonal element are also studied until all important relationships have been identified.
3. The interactions judged under point two above to be of importance for further scenario selection are then summarized under the heading "Scenario-generating event, process or data uncertainty". Based on the important interactions, events, processes or data uncertainties judged to be capable of making it impossible for the safety function to be maintained and occurrence of the alternative evolution are then identified. In connection with this identification, the way in which external FEPs, EFEPs, presented in Table 3-2 and Table 3-3 can affect the system is studied.

[2] Certain safety functions will not be maintained during the entire analysis period even for the reference evolution, which is described in section 6.7. This is the case, for example, when glacial groundwater penetrates down to repository level. However, this is a part of the expected evolution and no alternative repository evolutions apart from the reference evolution are generated by these events.

Table 7-1. Components, safety functions and performance indicators.

Component	Safety function	Performance indicator
Waste	Limited quantity of activity	Activity in repository part
Geosphere	Low flow in repository parts	Limited gradient Limited fracture transmissivity
Engineered barriers – hydraulic function	Limited advective transport	Hydraulic conductivity of concrete walls Hydraulic conductivity of bentonite Temperature (silo) Temperature (concrete) Gas pressure in silo
Engineered barriers – chemical function	Good sorption	Reducing conditions High pH Expected concentrations of complexing agents Available sorption surface area
Biosphere	No wells	Location in relation to shoreline

Section 7.6 starts with a compilation of the alternative repository evolutions and the scenario-generating events, processes or data uncertainties identified in previous sections. Based on this compilation, scenarios are then selected where a probability is assigned to the uncertainty judged capable of generating an alternative repository evolution. Based on the selected scenario, calculation cases and data can then be defined in Chapter 8. Each scenario description contains:

1. An introductory text where the scenario is presented based on the safety function that is not maintained and the more or less probable events, processes or data uncertainties that have been identified as leading to a repository evolution different from the reference evolution.
2. A discussion of the probability that the scenario will occur. The probability is assigned a numerical value if possible, but qualitative definitions such as "less probable than the main scenario" are also permitted. If numerical values cannot be assigned, the probability must be handled pessimistically in the risk evaluation, for example by setting a high probability.

Section 7.6 is concluded with a classification of the scenarios into three categories:

1. A main scenario based on the evolution of the repository and its environs described in the reference evolution.
2. A set of less probable scenarios that cover uncertainties that have not been evaluated in the main scenario. They are evaluated along with the main scenario in the final risk analysis. Combinations of less probable scenarios are also counted as less probable scenarios.
3. Consequences of human impact in a long-term perspective and scenarios that have not been assigned probabilities but are used to demonstrate the function of the repository are analyzed in the residual scenarios. The results of depositing too much activity in the repository are also studied as a residual scenario. In this residual scenario, all uncertainty in the radionuclide inventory is assumed to be distributed so that a higher average inventory is reached than that assumed in the reference evolution (and the main scenario). The residual scenarios also include a scenario where the effects of an abandoned unclosed repository are studied.

7.4 Probable repository evolution – main scenario

As described in the regulatory requirements cited in section 7.2, the main scenario should be based on a probable evolution of external conditions and realistic or, where justified, pessimistic assumptions with respect to the internal conditions. The reference evolution is described in detail in Chapter 6, and this description is therefore not repeated here. Since SFR 1 is located at a shallow depth and is expected to end up beneath the land during the analyzed period due to shoreline displacement (from having previously been located beneath the sea), the following must be taken into consideration:

- Due to a dynamic evolution of hydrological conditions, the discharge rates from and through the repository will change during the analysis period. As a result, releases from the near-field must also be studied under transient (or at least quasi-steady-state) conditions.
- A dynamic evolution the biosphere. The change is primarily driven by shoreline displacement and takes place during a relative short period of time. As a result, dose conversion factors obtained under the assumption that the system is in equilibrium cannot be used in the same way as under more steady-state biosphere conditions /Bergström et al. 2008/.

Since SFR 1 is not designed to isolate radionuclides but only to retard their outward transport, radionuclide transport calculations are relevant for the main scenario during the entire analyzed period. Just as in the SR-Can safety assessment, which was performed for a KBS-3 repository but covers the same period and a repository on the same site (Forsmark), the main scenario must be divided into two variants that describe different climatic evolutions that cannot be assigned relative probabilities. The main scenario is divided into two variants. The first is based on reconstructed conditions from the latest glacial cycle, the Weichselian glaciation. The second describes a future climate evolution when anthropogenic impact has led to an enhanced greenhouse effect and the present-day temperate period is assumed to extend over a longer period. In addition to these climatologically separate variants, a less probable scenario is described later in the report (section 7.6.2) where the climate is colder and drier, leading to an earlier freezing of the repository than in the Weichselian-based variant.

Under periglacial conditions, continuous or discontinuous permafrost is assumed to be the dominant biosphere type in the area, see the reference evolution. Under temperate conditions, the surface ecosystems will be dependent on the location of the shoreline. During a part of the period, SFR 1 will be located under water, just like today, and during other parts of the period terrestrial ecosystems will predominate. When glacial conditions prevail there is assumed to be no outflow of radionuclides from the repository and no dose calculations are performed for these periods. The connection between the climatological domain and the prevalent ecosystem is described in the reference evolution, Chapter 6.

7.4.1 Variant based on Weichselian-based climate evolution

The climate evolution in the main scenario's Weichselian-based variant is based on a reconstruction of the conditions during the latest glacial cycle, including the Weichselian glaciation /Vidstrand et al. 2007/. The detailed climate evolution described in the reference evolution, section 6.2.2, has been purged here of short fluctuations /Vidstrand et al. 2007/ to give a clearer picture and more continuous periods with the different climate domains, see Figure 7-1.

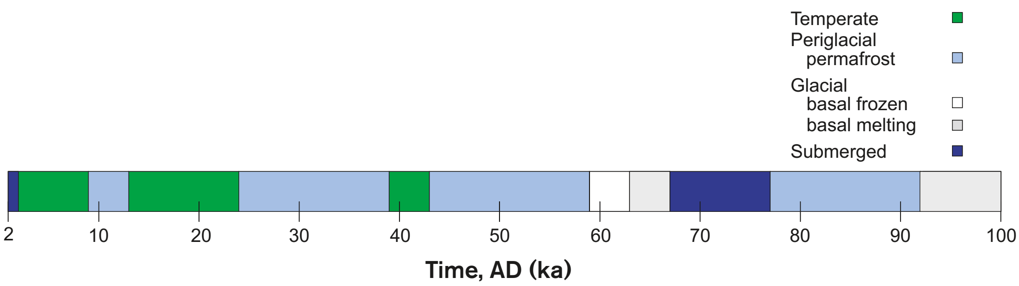

Figure 7-1. *Climate evolution according to the main scenario's Weichselian variant based on a reconstruction of the conditions during the latest glacial cycle.*

Climate evolution

The Weichselian-based variant starts with a period of temperate climatic conditions that lasts for 8,000 years. Then comes the first periglacial period where permafrost conditions dominate. This period is followed by a return to temperate conditions, which are gradually supplanted by permafrost conditions. Extended periglacial periods with deep permafrost exist between about 42,000 and 56,000 years and between about 75,000 and 90,000 years post-closure. The permafrost and the frozen ground reach down to the repository during these periods, see Figure 6-3. The temperature in the bedrock during the first permafrost period with deep permafrost falls to about –10°C and during the second period to about –5°C /Vidstrand et al. 2007/. The maximum depth of the permafrost is around 250 m and is reached after 50,000 years, see Figure 6-3.

After around 60,000 years the ice sheet advances over the Forsmark region in this scenario variant. The second, longer glacial period ensues after about 90,000 years. Permafrost growth stops when the ice sheet covers the site and begins to grow thinner. This trend, with gradual development of more dominant and longer permafrost periods and glaciation, is a result of the increasingly cold climate during the glacial cycle.

As the ice sheet advances, the upper part of the rock is insulated from the cold climate, and eventually basal melting takes place beneath the ice. In the Weichselian-based variant of the main scenario, the Forsmark region is covered with ice for a total of about 30,000 years. Basal melting dominates during this time. The maximum thickness of the ice in the Forsmark region is about 2,900 m. Permafrost prevails in this variant for more than 40,000 years (of the analyzed period).

7.4.2 Variant based on increased greenhouse effect

The main scenario's greenhouse variant describes a climate evolution that includes human-induced climate change /IPCC 2001, BIOCLIM 2004, IPCC 2007/, above all due to emissions of greenhouse gases. The main scenario's greenhouse variant is based on the greenhouse variant described in section 6.2.2, except that like the Weichselian variant, this variant has been purged of short fluctuations to give a clearer picture and more continuous periods with the different climate domains, see Figure 7-2. In this scenario the average temperature increases globally and in Sweden due to an increased greenhouse effect. This also leads to a total melting of the Greenland ice sheet.

Climate evolution

In the greenhouse variant it is assumed that the first 50,000 years will be temperate, followed by the first mild period of the climate evolution in the Weichselian variant. The start of the subsequent glaciation is accordingly assumed to be shifted forward in time, and the glaciation periods during the coming 120,000 years will be shorter than in the main scenario's Weichselian variant. This results in 70,000 years of temperate climatic conditions, aside from a short initial permafrost period at 60,000 years. Periods with heavy permafrost start around 75,000 years into the scenario. Permafrost prevails in this variant for just under 30,000 years. The first glaciation period occurs at around 110,000 years. In this variant, glacial conditions prevail for about 30,000 years and the permafrost reaches down to a maximum depth of 250 metres. An ice sheet covers the site after around 110,000 years.

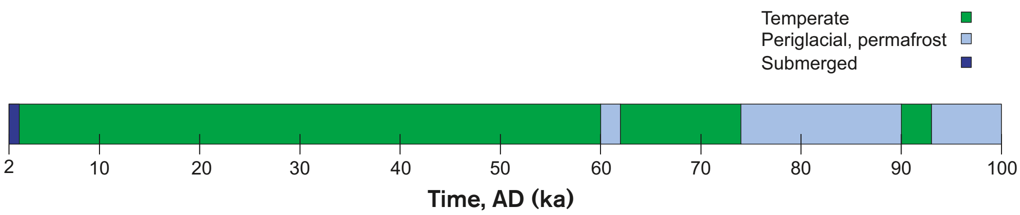

Figure 7-2. *Climate evolution according to the main scenario's greenhouse variant.*

7.5 Alternative repository evolutions derived from safety functions

Uncertainty in the evolution of the repository, as described in the reference evolution and in the variants of the main scenario that have been presented, is handled by defining a number of additional possible evolutions. As a point of departure for this, factors that make it impossible for safety functions to be maintained are studied based on the criterion "deviates from the reference evolution".

7.5.1 Safety function "Waste – Limited quantity of activity"

The safety function "Limited quantity of activity", Table 7-2, refers to the activity of different radionuclides that are stored in each repository part. The quantity referred to relates to the prevailing radiation protection conditions for SFR 1.

Status of the safety function in the reference evolution

The inventory given in Table 8-1 is assumed to apply in the reference evolution with no uncertainty interval.

Identified interactions with a bearing on the safety function

The inventory in the different repository parts is identified as diagonal components 1–4 in the repository interaction matrix, where the inventory may be found both dissolved in the aqueous phase and sorbed to various solid phases in the repository parts or in other parts of the repository system.

Even the realistic forecasts of the nuclide inventory which the existing safety assessment is based on and which are included in the main scenario show that the inventory limitations according to Table 5-1 will be exceeded for some nuclides in some of the repository parts. A number of circumstances could conceivably lead to the forecast quantity of activity being exceeded. These circumstances can be divided into mistakes during repository operation and inadequate knowledge of the deposited radionuclide inventory.

1. The forecast includes a measure of uncertainty, and it is possible that future waste production will exceed the forecast inventory. Since the current inventory and future deposition are continuously monitored by the authority and SKB, the risk that the deposited quantity of waste will exceed today's conditions without advance approval is not considered relevant for this analysis.
2. Different types of waste will be kept in different repository parts in SFR 1. It is conceivable that waste is placed in the wrong repository part for some reason. To prevent this, all production, transport and deposition of waste takes place under controlled forms. Furthermore, the system is built so that certain types of waste packages cannot be deposited in all repository parts, which provides a built-in safety factor. Documentation provides traceability so that misplacement can be discovered and, if possible, corrected.
3. The activity in the waste is calculated based on the activity of certain key nuclides. The activity of other nuclides can then be estimated by the use of correlation factors. Correlation factors are associated with uncertainties, which leads to a corresponding uncertainty in the nuclide inventory. A compilation /Torstenfelt 2007/ quantified these uncertainties.

Table 7-2. Safety functions and performance indicator for the component "Waste".

Safety function	Performance indicator
Limited quantity of activity	Activity in repository part

Scenario-generating event, process or data uncertainty

Uncertainty in correlation factors /Almkvist and Gordon 2007/ is deemed to be the most probable reason why the activity quantity in the repository could be exceeded. SFR 1 is licensed for a total activity of 10^{16} Bq. Based on today's forecasts of the inventory after 50 years of reactor operation, a realistic inventory is assumed for SFR 1 amounting to $1.5 \cdot 10^{15}$ Bq. A possible case for illustrating the effect of an inventory in excess of that forecast is to scale up the inventory so that the alternative inventory has a total activity of 10^{16} Bq. This inventory is judged to include all uncertainties in the total inventory, even those caused by uncertainty in correlation factors according to point 3 above. Of the radionuclides presented in the compilation of uncertainties /Torstenfelt 2007/, the nuclides Se-79 and Ag-108m are judged to be both relevant to long-term safety and have uncertainty intervals that are not covered by the scaled-up inventory. Whether or not this uncertainty affects the final result is discussed in Chapter 10.

The uncertainty in radionuclide inventory that is attributed to uncertainty in correlation factors could be regarded as an uncertainty in the initial state of the repository and be handled in the main scenario. Based on the current state of knowledge, the uncertainties are symmetrically distributed around the central value. Since radionuclide releases, for the conceptual model used to describe repository function, scale linearly versus the inventory, this uncertainty does not affect the mean dose/risk from the repository in probabilistic simulations. In order to minimize the number of realizations in the probabilistic simulations, it is more appropriate to study a maximum radionuclide inventory as a separate scenario.

The residual scenario "alternative inventory" is presented in section 7.6.8.

7.5.2 Safety function "Geosphere – Low flow in repository parts"

The safety function "Low flow in repository parts", Table 7-3, concerns the regional flow through rock and fracture zones. The influence of the safety function on the repository parts is identified in the geosphere interaction matrix[3] via the state variable for Hydrology, GEO11 (which also includes water in different parts of the system). This safety function only applies to the geosphere and its ability to maintain favourable hydrological conditions in the repository. The influence of the hydrological conditions on radionuclide transport in the repository areas is treated with the safety function "Limited advective transport".

The groundwater flow through (and near) the repository is of great importance for the function of SFR 1 as a whole. This is particularly true for the BLA repository, which in principle lacks other retarding functions than low flow, while the other repository parts are designed with hydraulic barriers. Since the hydraulic barriers are of great importance, separate performance indicators are defined for them, which are analyzed in the section for the safety function "Limited advective transport".

The two performance indicators "gradient" and "fracture transmissivity" together give the groundwater flow. These two indicators are therefore discussed together.

Limited fracture transmissivity and limited gradient

The flow through the different repository parts is dependent on the transmissivity of fractures in the rock and how they connect to the repository area. Since the fracture transmissivity is inhomogeneously distributed in the rock around SFR 1, the local flow will also be.

[3] The geosphere interaction matrix is presented in Appendix D. Interactions and states identified in the matrix are designated in the text as GEOXX.YY, where XX and YY represent row and column in the matrix. The abbreviated form GEOXX is used for diagonal components.

Table 7-3. Safety functions and performance indicators for the component "Geosphere".

Safety function	Performance indicator
Low flow in repository parts	Limited gradient
	Limited fracture transmissivity

The site of SFR 1 was selected partly because of the low hydraulic gradient. However, as is described in the reference evolution, the direction and size of the gradient changes due to shoreline displacement. Today, when SFR 1 is located beneath the surface of the sea, the gradient is slightly upward-directed. At 3,000–4,000 AD, the gradient is expected to increase, be more horizontal and also more controlled by the local, rather than the regional, topography. The importance of the gradient is, however, included in the discussion of the regional flow (see below).

Status of the safety function in the reference evolution

It is observed in section 6.4.2 that the site for SFR 1 was selected in part because it is situated in an area with a limited hydraulic gradient and limited fracture transmissivity. No major changes in fracture transmissivity are expected in the reference evolution. Minor changes in the hydraulic gradient occur as a consequence of shoreline displacement. The hydraulic gradient is greatly altered as the ice sheet advances and retreats.

Identified interactions with a bearing on the safety function

GEO(1-4).11 concerns hydraulic interaction between the flow in different repository components and the surrounding regional flow. These interactions are included (and are therefore always taken into account) in the hydrological models, where the repository parts are explicitly integrated.

GEO(5,6).11a,c concerns the influence of the tunnels, the plugs and boreholes on groundwater flow under saturated conditions. Groundwater flow under saturated conditions is included (and is therefore always taken into account) in the hydrological models, where tunnels and plugs are explicitly integrated.

GEO8.11a concerns how the near-field rock around tunnels and repository components influences groundwater flow under saturated conditions. Groundwater flow under saturated conditions is included in the hydrological models (and is therefore always taken into account), where the near-field rock, tunnels and repository components are explicitly integrated. Deviations from the main scenario could occur as a result of earthquakes, when old fracture zones can take on great importance. This occurs via GEO14.8 and REP8.

GEO9.11 concerns the influence of the regional rock on the flow in the repository. The relevant parameters are frequency, aperture and connectivity of the fractures in the surrounding rock. Water flow under saturated conditions is included in the hydrological models (and is therefore always taken into account). Deviations from the main scenario could occur as a result of earthquakes, when old fracture zones can take on added importance. This occurs via GEO14.9 and REP9.

GEO10.11 concerns how the groundwater composition influences the groundwater flow. Differences in the density of the groundwater influence the driving force. An introductory study /Stigsson et al. 1998/ showed, however, that this was of secondary importance for SFR 1, which is relatively shallow, and the effect is therefore neglected in further analyses. This effect is also considered to be of minor importance for the current safety-function-driven scenario analysis. Theoretically, concentration differences can also give rise to osmosis, but this effect can be neglected entirely.

GEO12.11b concerns two-phase flow in the geosphere. This is not included in the hydrological models, but studies have been performed to determine whether two-phase flow affects the hydraulic conditions. The conclusion was that the gas that is generated passes through the geosphere relatively unhindered and has little effect on the local flow pattern /Thunvik and Braester 1986, Berger and Braester 2000/.

GEO13.11 concerns phase transitions in the groundwater due to temperature changes (in principle freezing and thawing). This interaction is considered to be of importance under glacial conditions and is handled in the main scenario.

GEO14.11 concerns how hydrological conditions are affected by the stress state in the repository. The effect of this interaction is judged to be limited in comparison with other effects of changed stress conditions.

GEO17.11 concerns the hydrological boundary conditions given by the biosphere. These conditions, in the form of infiltration on land and pressure beneath the sea, are included in the hydrological models, for example via shoreline displacement. This interaction is handled in the main scenario.

GEO18.11 concerns hydrological boundary conditions on a regional scale. These conditions (e.g. inflow and regional gradient) are handled in the regional hydrological model.

Scenario-generating event, process or data uncertainty

Based on the above analysis of the geosphere interaction matrix, GEO8,9.11 and GEO 13.11 are judged to be capable of deviating from the reference evolution to such an extent that they can generate scenarios. These two interactions require external influence via EFEPs, Table 3-2 and Table 3-3.

1. EFEPs in the category “Tectonics” affect GEO14, see Table 3-2. An earthquake could, via GEO14 and GEO14.8,9, change the fracture characteristics of the rock in such a way that the safety function can no longer be maintained. The earthquake scenario is presented in section 7.6.1.
2. EFEPs in the category “Climate change” affect GEO10, GEO11, GEO13 and GEO14, see Table 3-2. Glacial conditions could, via GEO13 and GEO11.13, change the permeability conditions in the geosphere so that the safety function can no longer be maintained. Glacial conditions are normally handled in the main scenario, but for a conceivable situation with discontinuous permafrost cover (for example a talik), a scenario with increased groundwater flow is required. The scenario “Taliks” is presented in section 7.6.4.

7.5.3 Safety function “Engineered barriers – Limited advective transport”

Limited advective transport is a safety function for the hydraulic function of the engineered barriers. By “engineered barriers” is meant (see Chapter 5) the concrete backfill that surrounds the waste packages in the silo, BMA and BTF, sand/bentonite backfill in the top and bottom of the silo repository, and the bentonite that surrounds the silo repository. There are no engineered barriers in the BLA repository. Table 7-4 presents the performance indicators that have been selected for the safety function.

In the repository interaction matrix[4], concrete backfill and buffer are represented by the diagonal components REP6, REP7 and REP8. The hydraulic function of the engineered barriers affects the repository’s hydrological conditions, REP11, and radionuclide transport, REP11.16.

[4] The repository interaction matrix is presented in Appendix D. Interactions and states identified in the matrix are designated in the text as REPXX.YY, where XX and YY represent row and column in the matrix. The abbreviated form REPXX is used for diagonal components.

Table 7-4. Safety functions and performance indicators for the component "Engineered barriers – hydraulic function".

Safety function	Performance indicator
Limited advective transport	Hydraulic conductivity of concrete walls
	Hydraulic conductivity of bentonite
	Temperature (silo)
	Temperature (concrete)
	Gas pressure in silo

The following text presents, for each performance indicator, the interactions that are deemed important (a priority different from green in the repository interaction matrix) for the safety function and that can make it impossible for the safety function to be maintained.

Hydraulic conductivity of concrete walls (BMA and BTF repositories)

The influence of the performance indicator on the hydraulic flow in a resaturated system is identified as REP(4,7).11a, water flow. The explanatory text about this interaction states that this interaction is affected by the dimensions, porosity, permeability and homogeneity of the concrete backfill.

Status of the safety function in the reference evolution

A greater water flow is expected through the concrete tanks in the BTF repositories than through the concrete moulds in the BMA repository. The higher water flow leads to a more rapid chemical degradation of the concrete. This is expected to occur after the first 1,000-year period and lead to a great change in porosity and hydraulic conductivity, see section 6.5.4.

No great change in hydraulic conductivity is expected in the BMA repository due to mechanical or chemical degradation of concrete. However, a substantial reduction in hydraulic conductivity is expected due to the fact that the concrete cracks when it freezes and thaws in connection with the permafrost that is expected to reach down to repository depth in 23,000 AD at the earliest, see section 6.6.3.

Identified interactions that affect the safety function

REP10.(4,7) concern the impact of groundwater composition and degradation of organic material on concrete backfill (chemical degradation of concrete). Chemical degradation of concrete is studied in the reference evolution, and the results of this analysis are considered to be representative for the expected intervals in groundwater chemistry.

REP14.(4,7) concern cracking of concrete backfill due to changes in the repository's stress state, REP14. There are a number of possible interactions that could lead to this:

REP(1,2,3–8).14 concern changes in the stress state due to expansion/contraction of the barriers.

REP11.14 concerns a change in the repository's stress conditions due to hydraulic conditions, REP11. This could happen by freezing (phase changes in water), REP13.11, of pore water affected by REP13, Temperature. Other interactions that affect the repository's hydraulic conditions are studied as a part of the reference evolution.

REP12.14 concerns cracking of the concrete caused by increased gas pressure /Moreno et al. 2001/.

Scenario-generating event, process or data uncertainty

Based on the above interactions, REP14.(4,7) are judged to be able to deviate from the reference evolution to such a great extent that they can generate scenarios via External FEPs.

1. REP14, stress conditions, is influenced by EFEPs in the category "Tectonics" in Table 3-2. An earthquake could make it impossible to maintain the safety function "Limited advective transport". The earthquake scenario is presented in section 7.6.1, while the hydrological consequences of damage to the barriers are presented in 7.6.3.
2. REP13, temperature caused by EFEPs in the category "Climate change" in Table 3-2, affects stress conditions and damages the barriers in such a way that the safety function "Limited advective transport" can no longer be maintained. This is handled in the reference evolution, but due to uncertainty in the given climate scenario a case with early freezing of the repository should be taken into account. The scenario "Early freezing of the repository" is presented in section 7.6.2, while the hydrological consequences of damage to the barriers are presented in 7.6.3.
3. Concrete backfill, REP6 and REP7, is also affected by EFEPs in the category "Initial defects" in Table 3-2. These are regarded in the same way as in the SAFE project /SKB 2001c/ as being covered by the selected data interval. Large undetected differences that lead to early release to ecosystems with great dilution have not been taken into account.

Hydraulic conductivity of bentonite

The influence of the performance indicator on the hydraulic flow in a resaturated system is identified as REP8.11a, water flow. The explanatory text about this interaction states that this is affected by the dimensions, porosity, permeability and homogeneity of the bentonite.

Status of the safety function in the reference evolution

Hydraulic conductivity in the bentonite is affected very slowly by the chemical reactions that take place, section 6.5.4. No other processes are expected under temperate conditions that have any appreciable impact on the hydraulic conductivity of the bentonite.

Bentonite regains its hydraulic properties after freezing, since its swelling capacity provides a self-healing effect. The concentration of calcium ions may be low during ice ages, and in combination with a sharply elevated groundwater flow, this could cause erosion of the bentonite, resulting in great changes in its hydraulic conductivity. In the reference evolution this is assumed to occur no earlier than 68,000 AD.

Identified interactions with a bearing on the safety function

REP9.8b concerns loss of bentonite from (the silo repository's) buffer due to expansion into other backfilled parts of the silo repository. This loss is limited by internal and external friction and has been taken into consideration in design.

REP10.8a,c,e,f concern chemical degradation of bentonite. The effect of chemical degradation of bentonite based on expected groundwater compositions is presented in the reference evolution, sections 6.4.4, 6.5.4 and 6.6.4 for the three different periods (the first 1,000 years, between 3,000 AD and 20,000 AD and after 20,000 AD). During the first two periods, the selected groundwater compositions accurately represent what can be expected. Modellings show that the bentonite is affected very slowly by reaction with groundwater of the expected compositions. For the period after 20,000 AD, there are periods when the water composition in the repository has been affected by glacial water. During this period, groundwater composition, water turnover and thereby also chemical degradation are more difficult to predict. It is therefore assumed in the reference evolution that degradation of bentonite is very extensive at the time of the ice sheet at around 68,000 AD. Based on this treatment in the main scenario, it is assumed that the interaction does not generate further scenarios.

REP11.8e concerns mechanical degradation of bentonite. The water flow is controlled by the hydraulic gradient over the repository. The hydraulic gradient is low and well defined up to the period for the first glaciation. The hydraulic gradient is greatly altered as the ice sheet advances and retreats. It is assumed that the bentonite is eroded away during the first glaciation. Based on this treatment in the main scenario, it is assumed that the interaction does not generate further scenarios.

REP14.8, redistribution of bentonite. This interaction is handled as REP9.8 when redistribution requires access to new volumes.

REP15.8 concerns the effect of microbial activity on bentonite. Direct effect of microbial activity on bentonite can be neglected. There is in principle nothing in the active component of the bentonite (montmorillonite) that could serve as an energy source for microbes.

REP18.8a,d concern bentonite loss in the silo repository when bentonite expands into fractures (linked to GEO8.1) and cavings/rock fallout (linked to GEO14.1). Penetration of bentonite into fractures takes place to a very limited extent, since the fracture apertures are small and there is a shear resistance caused by the friction between the bentonite and the surface of the fracture /SKB 2006f/.

Scenario-generating event, process or data uncertainty

Of the interactions presented above, no events, processes or data, aside from those included in the reference evolution, have been assumed to affect the safety function.

Buffer, REP8, is also affected by EFEPs in the category "Initial defects" in Table 3-2. These are regarded in the same way as in the SAFE project /SKB 2001c/ as being covered by the selected data interval. Greater undetected differences that lead to early release to ecosystems with great dilution have not been taken into account.

Temperature

Temperature is defined in the interaction matrices for both the repository and the geosphere as REP13. The influence of temperature on the diagonal element "Hydrology"[5], REP11, takes place via REP13.11, which represents phase changes in the water phase. The diagonal element "Hydrology" in turn influences:

The stress state in the repository, REP14, via interaction with water pressure, REP11.14. The stress state in the repository can cause cracking of different concrete components, REP(1,2,4,6,7).14 and affect the stress state in the geosphere via REP14.17 and REP14.18.

Other interactions between the water flow and other components REP10.(1,2,8–10,12,15,16) are taken into account in the reference evolution.

Status of the safety function in the reference evolution

The temperature in the repository is determined by the exchange of heat with the surrounding rock and groundwater, which is in turn controlled by prevailing climatic conditions. Bentonite is assumed in the reference evolution not to freeze until at –5°C.

In the reference evolution's two variants of climate evolution, the Weichselian-based and the greenhouse-based, this does not occur until 23,000 AD and 73,000 AD, respectively.

[5] "Hydrology" in the interaction matrix also refers to the water phase in the different repository components and not just flow.

Identified interactions with a bearing on the safety function

There are few heat-generating processes in SFR 1, and for all intents and purposes the temperature of the repository will be determined by the exchange of heat with the surrounding rock and groundwater.

Scenario-generating event, process or data uncertainty

REP13, temperature caused by EFEPs in the category "Climate change" in Table 3-2, affects the safety function "Limited advective transport – Temperature". The scenario "Early freezing of the repository" is presented in section 7.6.2.

Gas pressure in silo repository

The influence of gas is identified in the interaction matrices for the repository as REP12. The safety function only concerns the silo repository.

Status of the safety function in the reference evolution

The dominant gas production in the silo is expected to take place in the initial phase of the assessment. In order for the gas to find its way out through the gas evacuation pipes and the sand/bentonite barrier in the top, a gas pressure must be built up equivalent to the opening pressure of the sand/bentonite barrier, which is around 15 kPa. Only a small gas pressure is required for the gas to be transported through concrete packages, porous concrete and the concrete structure. The chemical reactions that are expected up until the first ice age are not expected to lead to such great changes in the opening pressure of the sand/bentonite barrier that the gas pressure will be higher than around 15 kPa.

Identified interactions with a bearing on the safety function

REP(1,3,4,5,7).12, corrosion. The quantity and the composition of metals in the silo determine the corrosion mechanisms and the corrosion rate. This is crucial for how much gas can be formed and how rapidly this occurs. The presence of different metals can permit galvanic corrosion to occur. Iron is the dominant metal in the silo, but there is also a small inventory of aluminium and zinc. In a repository environment, iron is expected to corrode at a rate of 0.1–10 µm/year, while aluminium and zinc corrode much faster (~1 mm/year) /Moreno et al. 2001/.

REP(1,3–9).12, degradation of organic compoun ds. The quantity and composition of the organic materials in the silo determines the chemical and microbial degradation of these materials. It is primarily the degradation of cellulose that will affect the quantity of gas.

REP(1,3–9).12, gas flow. The dimensions and physical properties of the silo determine how gas can flow inside and out from the silo.

REP10.12c. The water composition in the silo is of importance for corrosion mechanisms and corrosion rates of metals and in this way determines the quantity and composition of the gas formed. The water composition in the silo is also of importance for chemical and microbial degradation of organic compounds and in this way determines the quantity and composition of the gas formed.

REP11.12c, two-phase flow. The water pressure inside the silo determines how gas can flow inside and out from the silo.

REP11.12d, expansion/contraction. The water pressure inside the silo determines what gas volumes can be formed.

REP15.12. The types and quantities of microbes in the silo will affect the gas quantity formed by degradation of materials and possible consumption of the gas formed.

REP16.12. Gas production due to radiolysis is negligible compared with the other ways gas is formed in the repository /Moreno et al. 2001/.

Scenario-generating event, process or data uncertainty

The processes (interactions) in the preceding section determine how rapidly a gas pressure can be built up in the silo. The total quantity of gas that can be formed is directly dependent on how much metals and organic materials have been deposited. A high gas formation rate therefore means that gas will only occur in an early phase in the evolution of the repository, while a low gas formation rate means that gas-related processes will occur over a long timespan.

However, none of the above processes will affect the safety function as long as the gas evacuation pipes work as they are supposed to, since all gas will be released at a low pressure.

A case where the gas evacuation pipes do not work as intended could, however, lead to the build-up of a high gas pressure inside the silo.

The gas evacuation pipes in the silo are designed to open and release gas at a pressure of 15 kPa. Higher pressures could be built up in the event of defective gas valves, however. This could be caused by:

1. The gas evacuation pipes are not installed according to specification.
2. There is a defect in the basic design.

In both of these cases, either the pipes could be defective from the start or their long-term function could be limited. A number of calculation cases with combinations of cases with defective gas evacuation pipes are presented in /Moreno et al. 2001/. The scenario “Gas-driven advection” is presented in section 7.6.6.

7.5.4 Safety function “Engineered barriers – Good sorption”

The chemical function of the barriers concerns sorption of radionuclides. Sorption is one of the most important retarding safety functions in SFR 1 and will occur in all repository parts as well as in the surrounding rock. But the greatest potential for sorption exists in the repository parts that contain cement. The safety function “Good sorption”, Table 7-5, has therefore been defined so that it only refers to sorption on cementitious material. This includes concrete walls, backfill grout and waste packages (affects radionuclide transport via REP(4,6,7).16 in the repository interaction matrix[6]), while sorption in bentonite, rock and conditioning material is exempted from the safety function. Some nuclides will not sorb under any conditions, in which case the safety function does not exist at all. But most radionuclides can be assumed to sorb very strongly under the conditions that exist in SFR 1. For many radionuclides, sorption is linked to the chemical environment in the repository, and the chemical environment is therefore an important performance indicator. Sorption presumes that the chemical environment (REP10 in the repository interaction matrix) is favourable, which is identified as REP10.16e.

The following analysis is therefore aimed at identifying what interactions can affect the groundwater composition.

[6] The repository interaction matrix is presented in Appendix D. Interactions and states identified in the matrix are designated in the text as REPXX.YY, where XX and YY represent row and column in the matrix. The abbreviated form REPXX is used for diagonal components.

Table 7-5. Safety function and performance indicators for the component "Engineered barriers – chemical function".

Safety function	Performance indicator
Good sorption	Reducing conditions
	High pH
	Expected concentrations of complexing agents
	Available sorption surface area

Reducing conditions

Reducing conditions are regarded as a part of groundwater composition, which is defined as REP10 in the repository interaction matrix. Its influence on the sorbing radionuclides in the system takes place via REP10.16.

Some of the radionuclides are redox-sensitive, and for most of these sorption is much weaker under oxidizing conditions. The redox criterion for the safety function "Good sorption" is therefore nuclide-dependent.

Status of the safety function in the reference evolution

Corrosion of iron and microbial activity create over a long time a reducing environment in the repository. When the ice sheet retreats, large quantities of oxygenated water can enter the repository. Reducing conditions will therefore not prevail with certainty during the whole period in SFR 1, which is located at a relatively shallow depth. Nor is it completely certain that reducing conditions will prevail in the repository in conjunction with permafrost.

Identified interactions with a bearing on the safety function

REP(1–9).10 concern the influence of the repository parts on water composition. A low redox potential in the repository is expected to be maintained as long as metallic iron and organic material remain, since iron reacts rapidly with oxygen, and organic material can be used in microbial processes that also consume oxygen. This promotes reducing conditions.

REP11.10a,c concern the influence of hydrology on water composition via advection and mixing as well as erosion. Far in the future, under glacial conditions, redox conditions will probably at least periodically be oxidizing. This is due to the fact that glacial meltwater is probably oxygenated and metallic iron will then probably have corroded away. Similarly, a large proportion of the organic material in the repository has been degraded. Under temperate conditions, microbial activity consumes the dissolved oxygen in infiltrating water (originally from rain and snow), but beneath an ice sheet, when no new organic material is produced, such processes may cease. Since the repository is located at a relatively shallow depth, reactions between dissolved oxygen in meltwater from an ice sheet and Fe(II) minerals in fractures and rock cannot take place to a great enough extent that all oxygen can be assumed to react before the meltwater reaches the repository. This means that most reducing substances, such as iron and organic material, are not available anymore and that it must be assumed that oxidizing conditions prevail at least periodically during a glaciation.

REP12.10a,b concern the influence of the gas phase on the redox properties of the groundwater. The main gases that are expected to be formed in the repository (carbon dioxide, methane and hydrogen) can only influence the redox conditions via microbial processes, which are dealt with in REP15.10 (see below).

REP13.10 concerns the influence of temperature on groundwater composition. Temperature effects, mainly due to climate change, are included in the main scenario.

REP15.10 concerns the effect of microbial activity on water composition. Under temperate and periglacial climatic conditions, microbial processes can be expected to produce an anoxic reducing groundwater. Under glacial conditions, the scope of the microbial processes at the surface is limited due to the absence of organic material (such as old leaves). The low temperature in the repository should also limit microbial processes in the repository volume.

REP17.10 concerns the influence of the transport of groundwater components through backfilled tunnels on the water composition in the disposal chambers. The redox effects should be the same as for the surrounding rock, see REP18.10 below.

REP18.10 concerns the influence of the rock volume on the water composition in the repository. The rock and fracture-filling minerals have a substantial Fe(II) content, as a result of which the groundwater tends to be reducing when it flows through the rock. This promotes reducing conditions.

Scenario-generating event, process or data uncertainty

Of the analyzed pathways above, REP11.10, "Influence of hydrology on water composition", is judged to be of importance under glacial conditions. The effect of REP15.10, microbial activity, is included in the reference evolution. Glaciation and permafrost are a part of the reference evolution and the main scenario and are not deemed to generate an additional scenario.

High pH

pH is a part of "Groundwater composition" (which also includes redox, ionic strength, salinity, solute concentration etc), which is defined as REP10 in the repository interaction matrix. Its influence on the sorbing radionuclides in the system takes place via REP10.16.

In general, cations sorb best at higher pHs, while the opposite applies to anions. But in natural waters, where organic ligands and carbonate occur, it is not certain that sorption increases with pH, since these ligands bind cations, which can reduce their sorption, and complexation increases with pH. However, there are plenty of calcium ions in the cement pore water. They can limit the concentration of organic ligands and carbonate by precipitation. Calcium can also compete with other cations when it comes to forming complexes. As long as the cement matrix is not degraded, calcium will be available and the pH in the pores will be higher than about 10.5. High pH is therefore an indication that the sorption properties in SFR 1 have been maintained due to the fact that the cement matrix has not been significantly degraded.

Status of the safety function in the reference evolution

Chemical degradation gradually causes the concrete material to lose its chemical properties and the pH declines. The degradation of the concrete in the silo and BMA repositories is judged to be slow as long as the concrete does not crack, for example via freezing, and a high pH will be maintained for a long time. In the BTF repositories, however, where cracking cannot be ruled out due to mechanical degradation, an earlier chemical degradation is expected, see section 6.5.4.

Identified interactions with a bearing on the safety function

REP(1–9).10 concern the influence of the repository parts on water composition. A high pH in the repository is expected to be maintained as long as cement remains. The life of cement is discussed in the reference evolution. This means that in the BLA repository, which contains the least cement of the repository parts, the pH will be lower than in the other parts.

REP11.10a,c concern the influence of hydrology on water composition via advection and mixing as well as erosion. Since inflowing groundwater is expected to have a neutral/low-alkaline pH, an increased groundwater flow through the repository can reduce the pH in the repository parts.

REP12.10a,b concern the influence of the gas phase on the redox properties of the groundwater. Of the main gases that are expected to be formed in the repository (carbon dioxide, methane and hydrogen), only carbon dioxide, which is an acid, can affect phased from the evolution described in the reference scenario, there are no other processes that can contribute to increased carbon dioxide formation.

REP13.10 concerns the influence of temperature on groundwater composition. Temperature effects, mainly due to climate change, are included in the main scenario.

REP15.10 concerns the effect of microbial activity on water composition. Microbial processes influence pH indirectly by carbon dioxide generation, which is handled in the reference evolution (see also above interaction).

REP17.10 concerns the influence of the transport of groundwater components through tunnels on the water composition in disposal chambers. The pH effects are judged to be the same as for the surrounding rock, see REP18.10 below.

REP18.10 concerns the influence of the rock volume on water composition. The rock with its fracture-filling minerals is an important pH buffer. As a result, the groundwater tends to become neutral or weakly alkaline when it flows through the rock. The influence of the pH in the repository is included in the reference evolution.

Scenario-generating event, process or data uncertainty

Of the above analyzed factors, only REP11.10a,c, "Erosion", is judged to be of importance and should be taken into account in further analysis with high groundwater flows that cause the barriers to degrade earlier. But this is already covered by the safety function "Limited advective transport" and is handled in the reference evolution.

EFEPs in the category "Initial defects – stray materials left" in Table 3-2 are considered to be able to influence REP10. But the effect of stray materials on pH is judged to be covered in the reference evolution.

Expected concentrations of complexing agents

Concentration of complexing agents is a part of groundwater composition (which also includes redox, ionic strength, salinity, solute concentration etc), which is defined as REP10 in the repository interaction matrix. Its influence on the sorbing radionuclides in the system takes place via REP10.16.

Degradation of the waste form (particularly cellulose) eventually leads to the formation of organic compounds (in the case of cellulose mainly isosaccharinic acid, ISA) that can form strong complexes with many radionuclides and thereby compete with sorption on the cement surfaces. It is therefore important that the quantity of these complexing agents be kept at low levels.

The high pHs and the high calcium concentration in the cement pores keeps down the concentration of a number of ligands by precipitation of calcium salts, mainly carbonate and oxalate, but also ISA. Many organic ligands, such as ISA, sorb on cement, possibly by complexation with calcium-rich solid phases. In summary, owing to its unique chemical environment, cement has proved to be excellent for controlling the concentration of ligands that could prevent sorption of a number of radionuclides.

Status of the safety function in the reference evolution

A limited initial quantity of complexing agents is ensured by SKB's and the regulatory authorities' inspections during the operating phase. In addition to the initial quantity, additional complexants will be produced by degradation of organic material throughout the studied period.

The forecast quantity of complexing agents is sufficiently low so that sorption is not judged to be affected to a greater degree than is contained within the uncertainties for the selected sorption data, see section 6.5.4.

Identified interactions with a bearing on the safety function

REP(1–9).10 concern the influence of the repository parts on water composition. Degradation of cellulose and the concentration of other ligands are discussed under the reference evolution. A faster degradation of cellulose than in the reference evolution would lead to a higher concentration of ISA during the repository's initial period.

REP11.10a,c concern the influence of hydrology on water composition via advection and mixing as well as erosion. Surrounding groundwater is expected to have a low concentration of organic ligands. An increased groundwater flow through the deposition areas thus leads to a lower concentration of complexing agents (as well as increased leaching and removal of radionuclides).

REP12.10a,b concern the influence of the gas phase on the concentration of ligands in the groundwater. Of the main gases that are expected to be formed in the repository (carbon dioxide, methane and hydrogen), only carbon dioxide can contribute to an increased carbonate concentration. Aside from the evolution described in the reference scenario, there are no other processes that can contribute to increased carbon dioxide formation.

REP13.10 concerns the influence of temperature on groundwater composition. Temperature effects on cellulose degradation are included in the main scenario.

REP15.10 concerns the effect of microbial activity on water composition. Microbial processes can generate a number of organic ligands. Most of them have low radionuclide affinities. A higher microbial activity than that in the reference evolution is not to be expected.

REP17.10 concerns the influence of the transport of groundwater components through tunnels on the water composition in disposal chambers. The effects should be the same as for the surrounding rock, see REP18.10.

REP18.10 concerns the influence of the rock volume on water composition. The only source of ligands in the rock is carbonates, which are present as fracture-filling minerals (calcite). An increased contribution of dissolved carbonate from the rock, in addition to that in the reference evolution, is not to be expected.

Scenario-generating event, process or data uncertainty

Only a more rapid degradation of cellulose than that described in the reference scenario could increase the concentration of ligands. The effect of this uncertainty is explored in the scenario "High concentrations of complexing agents", which is presented in section 7.6.5.

EFEPs in the category "Initial defects – stray materials left" in Table 3-2 are considered to be able to influence REP10. The effect on concentrations of complexing agents in the repository is, however, included in the case "more rapid degradation of cellulose".

Available sorption surface area

Sorption takes place on the surfaces of solid phases. Cement has a relatively high porosity, and several of the solid phases of which cement consists are amorphous and have a large specific surface area, which favours sorption. In time, several of the solid phases of cement can be transformed into more crystalline substances, which can diminish its sorption properties. Cement degradation processes result in precipitates that can reduce the porosity and thereby contribute to a reduction of the sorption capacity of the cement.

REP(4,6–7).16b describe how the properties of the cement components affect sorption surface area and thereby sorption capacity. Mechanisms that affect the stability of the cement components are described below. Besides cement, available sorption surface area can also be found in aggregate; this has not been taken into consideration.

Status of the safety function in the reference evolution

Chemical degradation gradually causes concrete materials to lose their chemical properties, resulting in reduced sorption surface area. The degradation of the concrete in the silo and BMA repositories is judged to be slow as long as the concrete does not crack, for example via freezing, and a large sorption surface area will be maintained for a long time. In the BTF repositories, however, where cracking cannot be ruled out due to mechanical degradation, an earlier chemical degradation is expected, see section 6.5.4.

Identified interactions with a bearing on the safety function

REP10.(4,6–7) concern cement degradation. Increased degradation can be brought about by a sharply increased groundwater flow. This could result in the transformation of all cement to aggregate. However, this affects the available sorption surface area less than the sorption properties. If the cement disappears the pH declines; this is discussed in the above section.

REP14.(4,6–7) describe cracking in cement components. This does not affect sorption properties or available sorption surface areas.

Scenario-generating event, process or data uncertainty

A sharply increased groundwater flow can reduce sorption capacity by speeding up cement degradation. This is, however, included in the reference evolution.

7.5.5 Safety function "Biosphere – No wells"

During the next millennium, all outward transport of radionuclides is expected to end up in the Baltic Sea, where dilution is great. Direct transport to the Baltic Sea could, from this perspective be regarded as positive, but is not desirable. However, in the planning and design of SFR 1 it was judged that a location beneath the Baltic Sea would be favourable from the viewpoint that no wells could be drilled through the repository or its discharge area before the shoreline had reached the point where the repository is beneath the land. For the extended period covered by this safety assessment (up to 100,000 years), however, the repository will be beneath the land during a large part of the analyzed period, which increases the probability that a well will be drilled through the repository or in its discharge area. It is for this reason the safety function "No wells", Table 7-6, has been defined.

By wells is meant drinking water wells and other types of wells (for example for geothermal heat, but also for geological investigations) that are positioned directly in the repository or in its discharge area. The hydrological effects of wells in, upstream of and downstream of the repository are investigated in the SAFE project /Holmén and Stigsson 2001a/. This study is used as a basis for the scenario definition in section 7.6.7 and in the following discussion.

Status of the safety function in the reference evolution

In the reference evolution it is assumed that wells for drinking water can be drilled in the repository or its discharge area during the periods the repository is expected to be located above the shoreline. This event is included in the main scenario and is taken into account in estimating the aggregate risk in the final summation of risk. The probability of wells in the repository's discharge area is presented in section 7.6.7. Wells drilled directly in the repository, intrusion wells, are handled separately and the probability of these wells is also presented in section 7.6.7.

Table 7-6. Safety functions and performance indicators for the component "Biosphere".

Safety function	Performance indicator
No wells	Location in relation to shoreline

Identified interactions with a bearing on the safety function

Wells drilled directly in the repository and in its discharge area are identified as GEO5.11c and could affect the hydrological conditions in the repository and its environs, GEO11 and REP11. As was shown in the SAFE project /Holmén and Stigsson 2001a/, this effect is extremely local and is not taken into account in the further assessment. Wells do, however, affect the outward transport of radionuclides from the repository via REP16, something which is taken into account in the further assessment.

Scenario-generating event, process or data uncertainty

Drinking water wells and other types of wells in the repository and its discharge area belong to EFEPs, category "Human-induced" in Table 3-2 and the FEP background report /Gordon et al. 2008/, and have the fact that wells are drilled as a scenario-generating event. The well scenario is presented in section 7.6.7, where probabilities that intrusion wells and wells in discharge areas will be drilled are included.

7.5.6 EFEPs related to residual scenarios

In the preceding part of section 7.5, safety functions have been used to identify alternative repository evolutions. For this, interaction matrices and external FEPs (EFEPs) valid for the main scenario and less probable scenarios, Table 3-2, have been used. Besides these EFEPs there are a number of EFEPs that have been judged to be related to the selection of residual scenarios and can therefore not generate scenarios with the chosen methodology. These EFEPs are taken into account by discussing for each group of EFEPs (initial defects, human actions and others) whether they can generate additional alternative repository evolutions than those arrived at earlier or whether they can be covered by the ones already arrived at.

EFEPs in the category "Initial defects"

EFEPs in Table 3-3 that relate to initial defects can be divided into two categories: "Unclosed repository" and "Unclosed boreholes".

Unclosed repository

An unclosed repository entails that the hydrogeological and chemical barriers do not function as intended and that the outward transport of radionuclides is considerably greater than for a functioning system. This cannot be analyzed within the main scenario and therefore requires an additional scenario: The residual scenario "Abandoned open repository" which is presented in section 7.6.11.

Unclosed (unsealed) boreholes

There are several observation holes with known positions that have been drilled from the repository out into the rock. Several of them intersect the different fracture zones that surround the repository /Axelsson and Hansen 1997/. There are, however, no holes drilled directly from rock vaults or the silo. Open holes will be plugged at repository closure, see section 4.2.5. It is conceivable that one or two holes may be imperfectly sealed. Unclosed boreholes have high hydraulic conductivity and offer low transport resistance, but their influence is nonetheless limited since there are no holes drilled directly from the rock vaults. The hydrogeological simulations performed in the SAFE project /Holmén and Stigsson 2001a/ and described in section 6.5.2 support the idea that no special quantitative analysis of the influence of unsealed boreholes is needed, since the effect of boreholes drilled in the repository and its environs is limited if no pumping takes place. No additional alternative repository evolution has therefore been identified; instead, uncertainties from the EFEP category "Unclosed boreholes" are included in the alternative repository evolution arrived at for the safety function "No wells". The scenario for "Wells" is presented in section 7.6.7

EFEPs in the category "Human actions"

The impact of future human actions needs to be analyzed. This includes both effects directly on those who perform the actions, and effects on the repository barriers as a consequence of the actions. In line with the principles used in the SAFE project, however, this is limited to actions that are performed without knowledge that the repository exists. There are a large number of human actions that can affect the repository's environs, but it is mainly different intrusions that could directly affect the repository's barrier functions.

Direct inadvertent intrusion

The probability of a direct inadvertent intrusion other than via a borehole is judged to be small. There are, for example, no known mineral deposits in the area /SKB 2006a/. Consequences of extensive rock cavern work or excavation of access tunnels will not be analyzed, since these intrusions are not regarded as inadvertent.

EFEPs in the category "Others"

There are two EFEPs in this category: "Deviant waste package" and "Flow through undetected boreholes". "Deviant waste package" is analyzed in the residual scenario "Alternative inventory" in section 7.6.8. "Flow through undetected boreholes" is included in the well scenario in section 7.6.7.

7.6 Selection of scenarios

The alternative repository evolutions that have been derived by assuming that the safety function cannot be maintained are shown in Table 7-7 along with the scenario-initiating events, processes or data uncertainties identified in section 7.5.

For each scenario-initiating event, process or data uncertainty that has been identified as being able to cause the repository to evolve in a way different from the reference evolution, scenarios are presented in sections 7.6.1–7.6.11. Besides events, processes or data uncertainties, these scenarios include the probability that the uncertainty will generate an alternative repository evolution. The name of each scenario corresponds to the scenario-initiating uncertainty in Table 7-7. Section 7.6.12 contains a compilation of the selected scenarios. Chapter 8 describes the calculation cases that have been selected to quantify the consequences of the scenarios.

7.6.1 Earthquake

The earthquake scenario is based on the assumption that an earthquake causes such great damage that several safety functions cannot be maintained, see Table 7-8. This section discusses the probability that an earthquake that damages the repository occurs. The hydrogeological conditions in a breached repository are discussed in section 7.6.3 "Defective engineered barriers".

Table 7-7. Safety functions and the events, processes or data uncertainties that make it impossible for the safety functions to be maintained.

Safety function	Scenario-initiating events, processes or data uncertainties	Earthquake	Early freezing of the repository	Defective engineered barriers	Talik	High concentrations of com-plexing agents	Gas-driven advection	Alternative inventory	Wells
Waste – Limited quantity of activity								×	
Geosphere – Low flow in repository parts		×			×				
Engineered barriers – Limited advective transport		×	×	×			×		
Engineered barriers – Good sorption						×			
Biosphere – No wells									×

Table 7-8. Safety functions that cannot be maintained in the scenario "Earthquake".

Component	Safety function
Geosphere	Limited regional flow
Engineered barriers	Limited advective transport

Introduction

Seismic activity has the potential to adversely affect the integrity of the repository system so that long-term safety is threatened. The seismic effect on a repository system is dependent on a large number of factors, which can be briefly summarized as follows:

- Frequency and magnitude of earthquakes.
- Structural and mechanical properties of the rock.
- Structural and mechanical properties of the repository system.

In order to assess the risk that a repository will be adversely affected by seismic activity, the repository system and the surrounding geological environment must be analyzed and modelled for the purpose of ascertaining how large seismic stresses the system can withstand. However, this does not lie within the framework of the analysis in the present section, which focuses on seismic activity.

Background

An earthquake is a rapid movement along a plane of weakness. The quake is caused by stresses in the Earth's crust, as a rule due to slow deformations over a long time. When the stresses have built up to the limit where the friction in the fracture is no longer able to resist the movement, an earthquake occurs. Earthquakes generally occur in existing fractures or fracture zones, since the bedrock contains a large number of planes of weakness with different orientations, and it is easier for the stress to be released along an existing fracture than to create a new one.

The size or magnitude of an earthquake depends on a number of circumstances such as the surface area of the fracture plane, the size of the displacement and the elastic properties of the rock. Since only the uppermost part of the Earth's crust is brittle, and since this part has a limited strength, there are limits to how large an earthquake can be. The largest earthquake ever measured had a magnitude of 9.5 on the Richter scale and thereby a displacement of several tens of metres along a fault several hundred kilometres in length and several tens of kilometres in width (depth).

Earthquakes have only been observed instrumentally for roughly 100 years. In many areas with a low frequency of large earthquakes, such as Sweden, this short observation period is a problem when it comes to estimating the earthquake risk. However, a clear correlation has been observed between the magnitude and number of earthquakes: an increase of one unit of magnitude corresponds to about a factor of ten fewer quakes. This correlation, called the Gutenberg-Richter relation, is widely used in assessing the earthquake risk.

Regional tectonics and regional stress conditions

By far most of the world's earthquakes occur along the edges of the large tectonic plates. Sweden is located far from a plate boundary (the closest one is the Mid-Atlantic Ridge) and is therefore to be regarded as an area with low seismic activity. Furthermore, Sweden is located in a very old and stable part of the Earth's crust known as the Baltic Shield, which means that seismic activity is generally lower here than in younger areas. With the knowledge we have today, it is highly unlikely that a large (magnitude 8-9) earthquake would occur in Sweden within the next few centuries.

In Sweden, the stresses at earthquake-relevant depths, below about 1 km, are dominated by tectonic stresses from the Mid-Atlantic Ridge, something which has been observed both seismically /Slunga 1991/ and in deep boreholes /Stephansson et al. 1991, Lund and Zoback 1999/. Closer to the Earth's surface, both borehole and overcoring measurements show that the stress state can vary considerably in both size and direction, but that there is nevertheless always a tendency for the horizontal stresses to be greater than the vertical ones /Stephansson et al. 1991/.

Postglacial land uplift is Sweden's dominant deformation process with vertical movements of up to more than one centimetre per year /Johansson et al. 2002/. Despite the large movements, land uplift does not significantly affect the stress state in the Earth's crust since the vertical movement takes place without resistance. Plate tectonics dominate the stress picture, which is shown clearly in the analysis of the focal mechanisms of Swedish earthquakes /Slunga 1991/. The effect of land uplift as a trigger of earthquakes has been discussed extensively, for example by /Johnston 1987, Fjeldskaar et al. 2000/ without any definite answer having been arrived at yet.

Earthquakes in Sweden

Earthquakes that damage buildings or other structures occur extremely rarely in Sweden. Small earthquakes occur almost daily, e.g. /Böðvarsson 2007, in the series 2002–2007/, and over a longer timespan it is not unlikely that a large quake could occur. The most recent large earthquake in Sweden had a magnitude of M_S 5.5 and occurred at the Koster islands in 1904. This is the largest quake we know of in Sweden, from both historical /Wahlström 1990/ and instrumental /Slunga 1991, 2007, Böðvarsson 2007, FENCAT 2007/ sources. Due to this low seismic activity, a very long observation time (hundreds of years) is needed to fully analyze earthquake behaviour. Since this is not possible for an assessment of seismic risk today, what is instead needed is a well-founded extrapolation of existing seismic and deformation-related data.

Seismic activity in Sweden exhibits considerable geographic variation, see Figure 7-3. It is higher in southwestern Sweden and along the coast of Norrland than in the southeast and the interior of Norrland. Furthermore, the postglacial faults in northern Sweden (e.g. Pärvie, Lansjärv) exhibit considerable seismic activity.

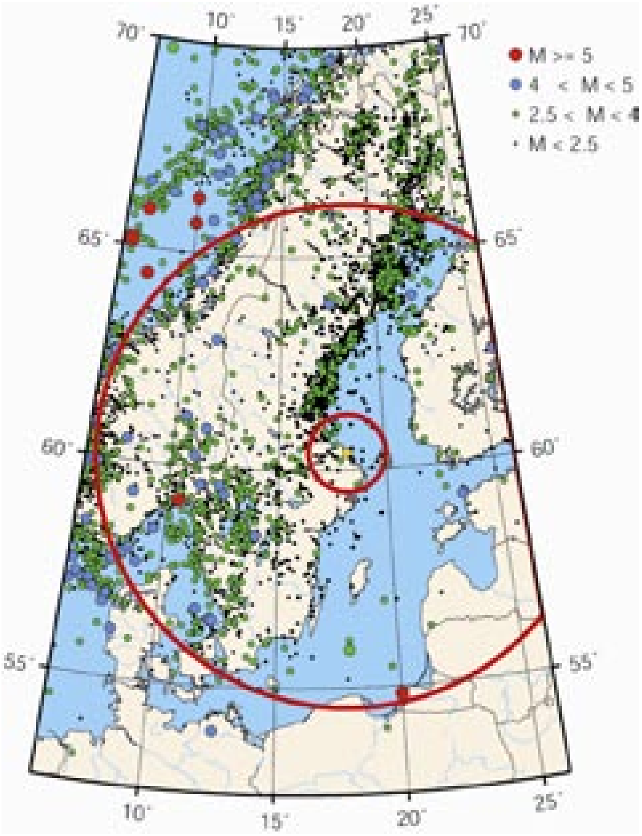

Figure 7-3. Seismic activity in Sweden with proximate area between 1904 and 2007 /Böðvarsson 2007, FENCAT 2007/. The Forsmark area is marked with a yellow square and the red circles show distances of 100 km and 650 km from Forsmark. The magnitudes in the Helsinki Catalogue have been homogenized to agree with SNSN's magnitudes /Slunga et al. 1984/. Note that the catalogues are not complete for Germany, Poland or the Baltic States.

The possibility of detecting small quakes has increased dramatically since the new Swedish National Seismic Network (SNSN) /Böðvarsson and Lund 2003/ was put into operation in 2000. On average three earthquakes per day are identified and analyzed today in Sweden.

Earthquakes in the Forsmark area

As is evident from Figure 7-3, southeastern Sweden has had very low seismic activity for the past century. This means that a statistical analysis of the earthquake frequency is highly uncertain. Since there is furthermore much to indicate that there is considerable episodicity in seismic activity in Sweden /Slunga 1991, Kijko et al. 1993/, it is unclear whether the relative calm in southeastern Sweden is a long-lasting phenomenon. However, no major postglacial faults have been demonstrated in the vicinity of Forsmark /Lagerbäck et al. 2005/.

In /Böðvarsson et al. 2006/, the SNSN (for example /Böðvarsson 2007/) and the Helsinki catalogues /FENCAT 2007/ were analyzed after the magnitude scales had been homogenized, in circles with a radius of 650 km around Forsmark and 500 km around Oskarshamn. Only the instrumental data from 1904 in the Helsinki Catalogue were used. It was found /Böðvarsson et al. 2006/ that the b-value, the slope of the Gutenberg-Richter distribution, was lower for the SNSN catalogue than for the Nordic data from the FENCAT catalogue by about 0.2 unit. For the Forsmark area, b_{SNSN}= 0.75 and b_{FENCAT}= 0.97. The two catalogues only overlap over one unit of magnitude, since there are few quakes above a magnitude of 3 in SNSN and few below a magnitude of 2 in FENCAT. The difference in b-value is probably also due to the fact that the SNSN catalogue only spanned six years and that the geometric distribution of stations in the Nordic region has been very uneven and variable since 1904. Time variations in the activity probably also play a role. The b-values given in /Böðvarsson et al. 2006/ are generally slightly lower than those reported by /Kijko et al. 1993/, who used the Helsinki catalogue from 1375–1989 and obtained 1.04 ± 0.05 for Sweden south of the sixtieth parallel. In /Skordas and Kulhánek 1992/, b = 0.8 was found for the area around Lake Vänern; in /Skordas and Wahlström 1988/, b-values of between 0.8 and 1.1 were estimated for the areas around Barsebäck and Ringhals; and in /Slunga et al. 1984/, b = 0.75 was reported for southernmost Sweden, south of 56.5° latitude.

Probabilities of earthquakes in the Forsmark area

As is evident, there are great uncertainties in the b-value determinations, and we therefore follow /Böðvarsson et al. 2006/ and base the analysis of the probability of earthquakes on data from most of Sweden (a radius of 650 km around Forsmark, according to /Böðvarsson et al. 2006/) and parts of Finland and Norway. We exclude, however, the relatively high activity along the Norwegian coast, since it is unclear whether it follows the same pattern as the Swedish activity. A Gutenberg-Richter relation spanning over five units of magnitude with a b-value = 0.81 was obtained in /Böðvarsson et al. 2006/. The a-value was determined to be 2.63 with the common logarithm of the number of quakes per year as the unit. Due to the relatively low b-value, we will overestimate the number of large quakes in relation to the number of small quakes, compared with studies that use a b-value of around 1.

Using the methodology described in /Böðvarsson et al. 2006/, probabilities have been calculated that earthquakes of a given magnitude will occur with a given distance of Forsmark during a given period. The results for a radius of 100 km and 10 km from Forsmark are shown in Table 7-9 and Table 7-10, respectively. It is evident from Table 7-9 that the probability of a magnitude 5 quake occurring within 1,000 years is relatively high, 61%, and that the probability of a magnitude 6 quake, 14%, is not negligible. If the radius is reduced to 10 km (Table 7-10), the probabilities of magnitude 5 and 6 quakes are 0.9% and 0.15%, respectively. Note that the extrapolation to 100,000 years is associated with very great uncertainties and does not take the effects of a glaciation into account.

Table 7-9. Probabilities in percent of earthquakes of magnitude M or greater within a distance of 100 km (with b=0.8). M is the magnitude of the quake, T is the expected time between two quakes (the recurrence time), and t is the exposure time, both in years (from /Böðvarsson et al. 2006/).

M	T	t = 10	t = 20	t = 30	t = 50	t = 100	t = 1,000	t = 100,000
3	27	30.95	52.32	67.08	84.31	97.54	100	100.00
4	168	5.78	11.22	16.35	25.74	44.86	99.74	100.00
5	1,061	0.94	1.87	2.79	4.6	8.99	61.04	100.00
6	6,696	0.15	0.3	0.45	0.74	1.48	13.87	100.00
7	42,250	0.02	0.05	0.07	0.12	0.24	2.34	90.62
8	266,579	0.00	0.01	0.01	0.02	0.04	0.37	31.28

Table 7-10. Probabilities in percent of earthquakes of magnitude M or greater within a distance of 10 km (with b=0.8). M is the magnitude of the quake, T is the recurrence time, and t is the exposure time, both in years (from /Böðvarsson et al. 2006/.

M	T	t = 10	t = 20	t = 30	t = 50	t = 100	t = 1,000	t = 100,000
3	2,666	0.37	0.75	1.12	1.86	3.68	31.28	100.00
4	16,820	0.06	0.12	0.18	0.30	0.59	5.77	99.74
5	106,127	0.01	0.02	0.03	0.05	0.09	0.94	61.03
6	669,617	0.00	0.00	0.00	0.01	0.01	0.15	13.87

Maximum movements caused by earthquakes

Earthquakes cause two types of deformations: the first is a static, permanent deformation of the bedrock, while the second is a dynamic, temporary deformation in the form of elastic waves. The static deformation decreases relatively rapidly from the focus of the earthquake, while the dynamic deformations are propagated much further.

From a seismic risk perspective there are a number of complications to take into account. The seismic load, both the dynamic and the static, can redistribute the stress field around an underground facility so that fractures and zones in the vicinity of the facility are reactivated. If such structures intersect the repository and are sufficiently large, a permanent shear may occur along them, resulting in a possible failure of the barriers.

Furthermore, it is an established view (e.g. /Bäckblom and Munier 2002/ and additional references therein) that underground structures are much more resistant to seismic damage than surface facilities due to the following:

- Underground structures are strongly coupled to the rock so there is less potential for the structures to attain their resonance frequency.
- Surface reflections, which amplify the amplitude of the waves, are avoided if the facility is sufficiently deep underground.
- The rock is considerably stronger than the overlying strata.

SFR 1 is, however, located relatively near the surface, which increases the risk that surface waves could damage the facility. In order to be able to assess what effects an earthquake of a given magnitude and at a given distance from the facility may have on long-term safety, further analysis and modelling are therefore required beyond the general rules related above.

Static deformations

It was shown in /Böðvarsson et al. 2006/ how the static deformations on the ground surface vary with the depth of an earthquake of magnitude 5 and with properties like the quake in Kaliningrad in 2004. The calculations were performed with a very simple elastic model of the Earth's crust and without taking into account the variations in the properties of the rock that often occur very close to the ground surface. At a depth of 800 m, the quake creates permanent deformations of at most 1 cm about 1 km from the fault, which entails maximum relative displacements of 2 cm over 2 km. At a depth of 3 km, the corresponding relative displacement is approximately 3 mm over more than 5 km, and for a quake at a depth of 12 km the maximum relative displacement is about 0.25 mm. A magnitude 5 quake at a realistic depth, below 2 km, thus causes relatively small static displacements. Larger quakes cause larger displacements, for example some of the postglacial quakes in northern Scandinavia have permanent displacements of over 10 m at the ground surface.

Dynamic deformations

The damage caused by seismic waves (the dynamic deformations) to buildings and structures depends in part on the amplitude and frequency of the waves, and in part on the structure in itself and how it is coupled to the ground or the rock. Traditionally in seismology the movement of the solid rock is stipulated without taking into account near-surface, loose rock or Quaternary deposits or structures. The most common measure of the damaging effect of an earthquake is the Peak Ground Acceleration (PGA) to which the rock can be subjected. PGA is used explicitly in the building codes of many countries and is often specified as a fraction of the acceleration due to the earth's gravity, g (9.81 m/s^2). Another measure that has begun to be used by the nuclear power industry in the USA is the Cumulative Absolute Velocity (CAV), which is an integrated measure and thereby takes into account the fact that a number of waves of high amplitude may be generated.

In /Böðvarsson et al. 2006/ it was estimated that a magnitude 5 quake with properties like the one in Kaliningrad in 2004 at a depth of 12 km gives a PGA of 0.05 g in competent crystalline rock. The equivalent maximum velocity is 16 mm/s, and the relative dynamic displacement over 500 m is 0.4 mm, much greater than the equivalent static displacement over the same distance. In /Wahlström and Grünthal 2001/, the earthquake risk in Scandinavia was studied using probability-based methods, and it was concluded that it can be expected with 90% probability that the PGA will not exceed 0.01–0.015 g in SE Sweden in 50 years. In /Slunga 1978/ it was calculated that with a probability of 0.01 per year the PGA can reach 0.007 g, and with a probability of 10^{-5} per year the PGA can reach 0.15 g in the Oskarshamn area, which should also be valid for the Forsmark area. According to /Slunga 1978/, it is mainly magnitude 6 quakes that account for the risks. Ground response spectra and acceleration spectra for probabilities of 10^{-5}, 10^{-6} and 10^{-7} per year are determined in Project Seismic Safety /SKI 1992/.

These figures for the probabilities of earthquakes and expected accelerations are dependent on what b-value is used. In Table 7-9 and Table 7-10, a b-value of 0.8 has been used, while a b-value of 0.69 was used in /Slunga 1978/. The latter gives slightly higher probabilities, but the differences can be regarded as falling within the margins of error.

Further handling for SAR-08

The probability that a quake will have an adverse effect on the repository system is dependent on the probability that a quake will occur within a given rock volume during a given period of time, as well as on the structural geology of the rock and how resistant the repository system is to earthquakes. There are, however, no quantifications of the tolerance of the repository system to quakes nowadays, nor any structural model detailed enough for this purpose that can serve as a basis for such calculations.

In order for an earthquake to damage critical repository components, however, they must be either intersected by or be located near structures in which the quake can occur. If it can be assumed that the repository volume around SFR 1 resembles the volume in the area being investigated as a candidate site for a final repository for spent nuclear fuel in Forsmark, there will be a relatively large number of structures in the near-field of SFR 1 in which quakes of up to a magnitude of 5 can occur. However, it is only if they intersect, or are located sufficiently close to, the repository that can cause damage.

The effects of earthquakes are only studied for the silo and BMA repositories. Both are intended for storing long-lived radionuclides and have concrete barriers that reduce the water flow in the repository. If these concrete barriers are breached by an earthquake, the water flow through the repository could increase, leading to an increased outward transport of radionuclides from the repository. Besides concrete barriers, the silo repository also has a self-healing bentonite buffer that reduces the hydraulic flow through the repository even if the concrete barriers are breached. The other repository parts are not included in the earthquake scenario, aside from barrier functions early in the analysis.

The method used to calculate radiological risk for the earthquake scenario is presented below. The calculations are based on three previous studies:

1. In /Bäckblom and Munier 2002/, the damage occurring in underground facilities was studied for earthquakes of different magnitudes. This study is used to determine what earthquakes could damage the repository[7].
2. In the SAFE project, the effects of damage to barriers caused by earthquakes on the hydraulic conditions in the silo and BMA repositories was studied /Holmén and Stigsson 2001a/. This study is used to calculate how quickly radionuclides in the repository are released after an earthquake.

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7 By damage is meant that the concrete barriers are breached so that the safety function "Limited advective transport" cannot be maintained.

3. A background report to SAR-08 calculates dose conversion factors for different biosphere types and thereby for different times, since the biosphere type varies with time /Bergström et al. 2008/. This study is used to calculate the radiological effects of radionuclide releases from a breached repository.

In /Bäckblom and Munier 2002/, several studies of earthquakes were summarized, including a study by /Dowding and Rozen 1978/ where 71 earthquakes with magnitudes of between 5.8 and 8.3 and focal depths (distance between epicentre on the surface and hypocentre) of between 13 and 40 km. The summary shows that there have been no reports of falling stones in underground tunnels, or of fractures in reinforced underground tunnels as a result of earthquakes that give rise to a surface acceleration of 0.2 g. Only a few incidents were found of shotcrete cracking in reinforced tunnels as a result of earthquakes that give rise to a peak ground acceleration of 0.25 g. Figure 7-4 summarizes the peak ground acceleration as a function of magnitude and distance to the fault that hosted the quake.

Based on this, the repository is judged to be intact even after an earthquake with a magnitude of more than 5 at distances of more than 10 km. Since this is based on generic data, however, it is cautiously assumed in the base variant of the earthquake scenario that earthquakes cause damage to the repository barriers at as low a magnitude as 5 and that this occurs for all earthquakes that occur within a radius of 10 km (despite the fact that an extrapolation of the magnitude 5 curve in Figure 7-4 suggests that even within a 10 km radius, quakes can result in such low ground accelerations that the repository remains unbreached). The base variant that is included in the estimate of the aggregate risk in Chapter 10 is supplemented by variants where the repository is assumed to be breached by quakes of magnitude 3, 4 and 6. These variants, which are also presented in Chapter 10, are calculated to analyze sensitivity to the assumption of critical quake magnitude.

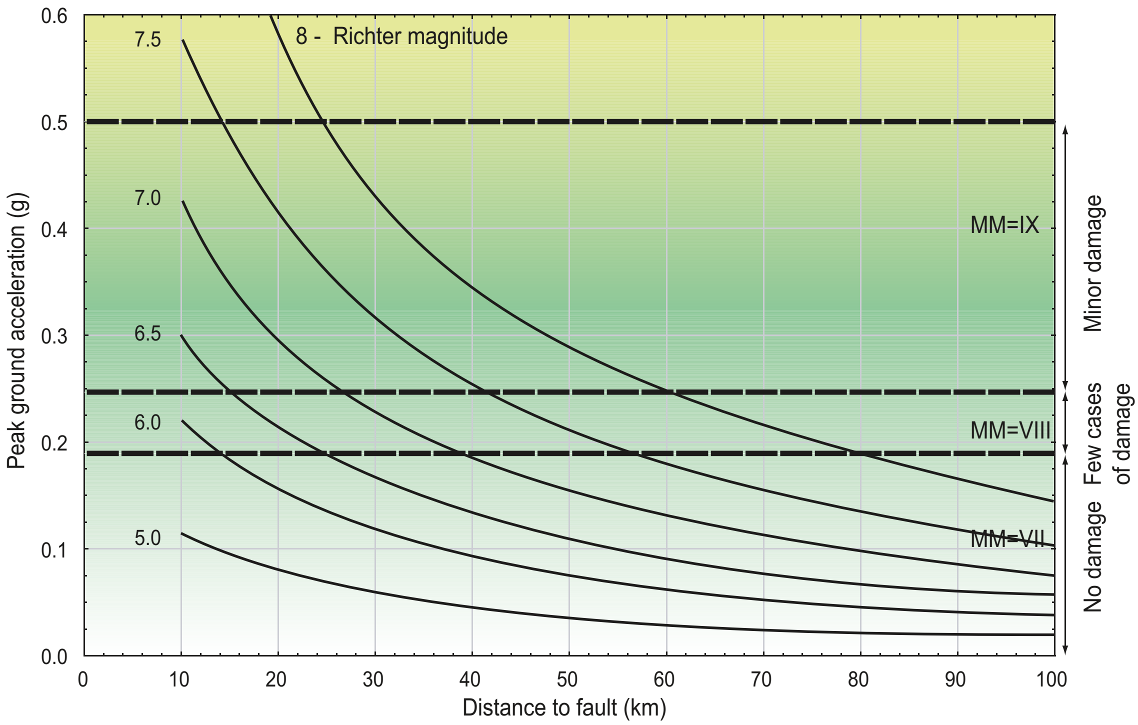


Figure 7-4. *Peak ground acceleration as a function of magnitude and distance to hypocentre. Originally from /Dowding and Rozen 1978/ and modified by /Bäckblom and Munier 2002/.*

Hydrogeological consequences of a repository breached by an earthquake

An estimation of the hydrogeological consequences of breached concrete barriers was carried out in the SAFE project /Holmén and Stigsson 2001a/ (see also section 7.6.3, "Defective engineered barriers"). In the study it was assumed that the barriers in the silo or BMA repository were breached and the resultant water flow through the repository was calculated. Based on the calculated water flow and the water volume stored in the repository's network of pores, the mean retention time for all water in the repository can then be calculated. Since the pore volume is largely located in pores that are not interconnected, this retention time is judged to be a pessimistic underestimate.

It is further assumed that the radionuclide inventory at the time of the damage is transported out of the repository with the water's turnover rate and that the geosphere does not offer any retention. In this way the radionuclide flow to the biosphere is estimated.

Since i) the pore network is in reality not interconnected, ii) most of the radionuclides in the repository can be assumed to sorb, iii) the distance to the fractures that are assumed to damage the repository is not taken into account, but rather the entire repository volume is assumed to be available for transport, and iv) the transport resistance in the geosphere is completely disregarded, this estimate of the radionuclide flow to the biosphere is deemed to be pessimistic.

Estimate of radiological risk for a breached repository

In the base variant of the earthquake scenario (see above), it has been assumed that a quake of magnitude 5 that occurs within a 10 km radius of the repository results in damage to the repository. Based on the calculated probabilities of earthquakes within a 10 km radius in the Forsmark area (Table 7-10), the frequency function *p(t)* for earthquakes of different magnitudes in the area at time *t* can be calculated.

By using the dose conversion factors that have been determined for release to the biosphere /Bergström et al. 2008/ and the radionuclide flow calculated on the basis of the water's mean retention time in the section above, it is possible to calculate dose *D(T,t)* at time *T* for an earthquake that occurs at time *t*, and finally also radiological risk with the following equation (see further /Bergström et al. 2008/.

$$R(T) = Risk\ Factor \int_0^T p(t) D(T,t)\,dt = Risk\ Factor \int_0^T \frac{e^{-t/MIBE}}{MIBE} D(T,t)\,dt \qquad (7\text{–}1)$$

where $p(t) = \frac{e^{-t/MIBE}}{MIBE}$ is an exponential distribution

where *MIBE* corresponds to the recurrence time for earthquakes according to Table 7-10 and *Risk Factor* to the conversion factor, 7.3%/Sv, that is recommended by the ICRP for radiological risk.

7.6.2 Early freezing of the repository

The scenario "Early freezing of the repository" is based on the assumption that an premature permafrost would cause the concrete barriers in the BMA repository to burst at an earlier point in time than the one studied in the two variants of the main scenario (the barriers in the BTF repositories have, according to the reference evolution, lost their safety function at an earlier point in time and the effect on the silo is, according to the reference evolution, limited since it has a bentonite buffer). Compared with the two climatological evolutions described in the main scenario, this evolution is judged to be less probable. It is, however, not possible to assign a numerical value to the probability of the scenario. It is therefore assumed for further analysis that the probability is one.

Scenario description

In this scenario the climatic conditions are exceptionally favourable for permafrost growth. The temperature is as low as in the variant of the main scenario that is based on a reconstruction of the Weichselian glaciation, but the climate is much drier. As a result there is no growth of the ice sheet and therefore no periods when the site is located below sea level due to isostatic changes. Nor is there any snow or vegetation, which further favours permafrost growth.

The climate is temperate during the first 8,000 years or so, followed by permafrost periods interrupted by brief temperate periods, Figure 7-5. In this scenario, permafrost conditions exist for a total of about 90,000 years. During all permafrost periods, the permafrost reaches deeper than the repository, Figure 7-6. Damage to the repository making it impossible for the safety function of the engineered barriers (section 7.5.3) to be maintained is not expected until the permafrost period, which extends past 23,000 AD and causes the BMA repository to lose its function /Emborg et al. 2007/.

Table 7-11. Safety functions that are not maintained in the less probable scenario "Early freezing of the repository".

Component	Safety function
Engineered barriers	Limited advective transport

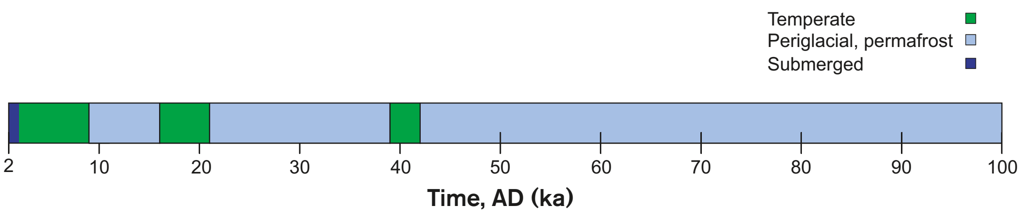


Figure 7-5. *Climate evolution in the scenario "Early freezing of the repository", based on assumptions of very favourable conditions for permafrost growth.*

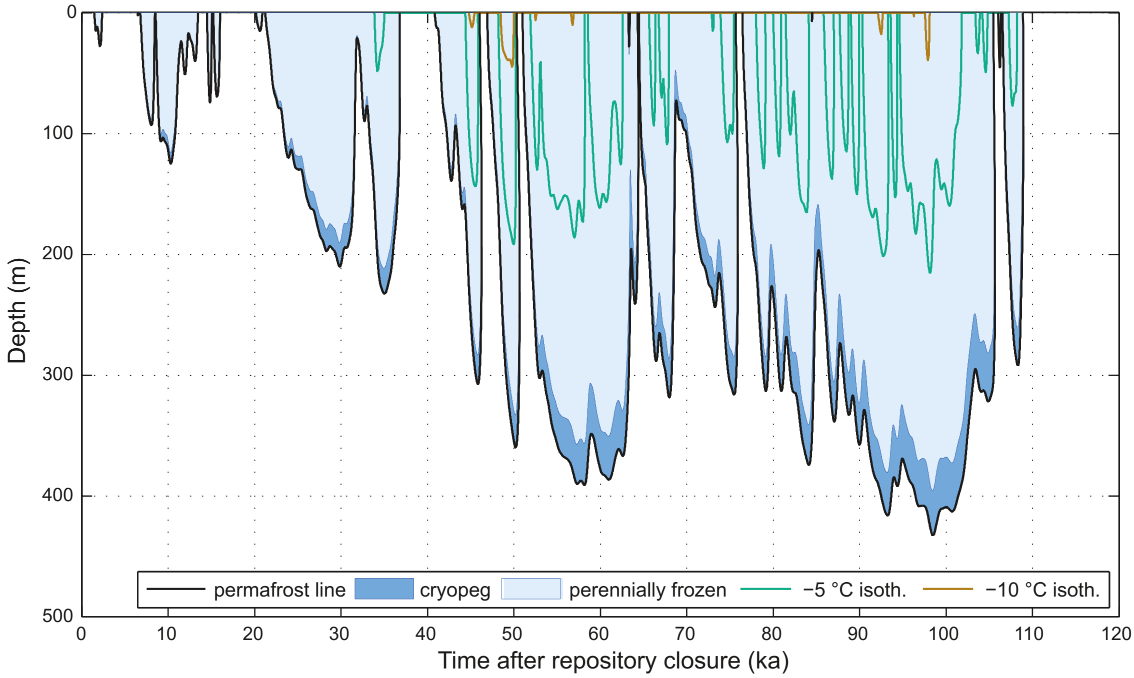


Figure 7-6. *Calculated permafrost depth and depth of the –5° C and –10° C isotherms at Forsmark for the scenario "Early freezing of the repository", based on 1D simulations of permafrost. For detailed information on these simulations, see /SKB 2006d, Vidstrand et al. 2007/.*

7.6.3 Defective engineered barriers

In the main scenario and the reference evolution it is assumed that the barriers degrade and their properties deteriorate. In the scenario "Defective engineered barriers" it is assumed that the safety function "Limited advective transport" cannot be maintained, causing the advective flow through the repository parts to increase more than in the main scenario.

It is considered most probable that high advective flows will occur if the barriers are breached by earthquakes, according to the scenario description in section 7.6.1, or burst due to freezing, according to the scenario description in section 7.6.2. Probabilities and scenario descriptions are given in sections 7.6.1 and 7.6.2, while the hydrological consequences of "Defective engineered barriers" are described in the following.

Flow through a breached or defective section in the BMA repository

The enclosure in the BMA repository is divided into different sections separated by concrete walls. As a sensitivity case in the hydrogeological calculations in the SAFE project /Holmén and Stigsson 2001a/, the effects have been calculated of a breach or collapse of one of these sections so that it completely loses its ability to limit groundwater flow. In the calculations, the section with the largest groundwater flow when the structure is intact has been regarded as being breached and having the same conductivity as the surrounding sand/gravel fill. The groundwater flow through the breached section increases because a portion of the groundwater flow in the surrounding sand/gravel fill will flow through instead of around the breached section. The intact sections of the enclosure are separated from the breached section by concrete walls. The groundwater flow through the intact sections therefore changes very little. Nor does the size of the groundwater flow in the surrounding sand/gravel fill change very much.

Even with an enclosure where one section is breached as described above, the total groundwater flow through the entire rock vault is affected very little for the BMA repository. According to the calculations, the total flow through the BMA repository increases less than 1 percent with one breached section compared with an intact repository. The effect of a breached section in the enclosure is primarily to redirect the flow in the sand/gravel fill. The detailed model predicts that the flow through the breached section comprises about 97 percent of the flow through the entire enclosure. The model also predicts that the flow through the breached section is between 30 and 37 times greater than the flow through an intact enclosure.

Flow through a breached section or in an completely collapsed silo repository

As a sensitivity case in the hydrogeological calculations, the effects of degradation of the silo enclosure and surrounding bentonite barriers so that they lose part of their ability to limit groundwater flow have been calculated /Holmén and Stigsson 2001a/. The groundwater flow through such a failed structure will be much greater than when the structure is intact. But since the encapsulation and the barriers will still have some capability to limit groundwater flow, the water flow will not be as great as that through a completely empty rock cavern. The simulations show that the total flow through a failed silo repository with a conductivity that is about 1.5 times greater than that of the surrounding rock is between 3 and 10 times (depending on the position of the shoreline) greater than the flow through an intact silo repository. The greatest flow increase takes place about 1,000 years after closure.

Table 7-12. Safety functions that are not maintained in the less probable scenario "Defective engineered barriers".

Component	Safety function
Engineered barriers	Limited advective transport

7.6.4 Talik

The talik scenario is based on the assumption that a discontinuity occurs in the permafrost cover above the repository under periglacial conditions and that the hydrogeological conditions change, Table 7-13.

During a periglacial period with extensive permafrost, the repository is theoretically either i) frozen or ii) located beneath a talik (a discontinuity in the permafrost) surrounded by permafrost. Conditions for talik formation above SFR are poor since there is no large depression in the topography above SFR 1 where a future lake might form. Permafrost growth above SFR 1 is also favoured by the fact that the local topography above SFR 1 slopes towards the north (albeit with a weak gradient). Because of this, a scenario where a talik is formed above the repository is considered to be less probable than the main scenario.

The scenario could occur anytime periglacial conditions prevail in the climate evolution assumed in the reference evolution. Since it has not been possible to specify the probability of the talik scenario, it is evaluated together with the main scenario with a probability of one.

7.6.5 High concentrations of complexing agents

The scenario describes the general consequences of a loss of sorption capacity in the chemical barriers, Table 7-14. According to the argument in section 7.5.4, high concentrations of complexing agents is judged to be the case which is most likely to lead to a loss of sorption capacity so that the safety function can no longer be maintained. The scenario also covers other events that lead to a loss of sorption capacity. However, the probability that the scenario will occur and input data (element-specific sorption data) are chosen to represent a case where the concentration of complexing agents is high.

Scenario description

Chemical and microbiological degradation of organic material in the repository can generate water-soluble organic compounds that can be bound to radionuclides, which alters conditions for retention of these radionuclides. The organic material consists for the most part of plastics, cellulose and bitumen. Degradation of plastics and ion exchange resins proceeds very slowly, and these materials have not existed long enough to be able to predict their life with any certainty or say anything about their degradation products in the repository.

Radiolytic degradation of ion exchange resins and bitumen can form sulphate and oxalate /Savage et al. 2000/. In previous SFR assessments /SKB 1991/ it was judged that the effect of degradation products from ion exchange resins and bitumen on sorption of trivalent and tetravalent radionuclides in concrete was small under the conditions expected to prevail in SFR 1. This judgement is supported by the conclusion drawn by /Savage et al. 2000/ after a review of results of experiments with degradation of ion exchange resins and bitumen.

Table 7-13. Safety functions that are not maintained in the less probable scenario "Talik".

Component	Safety function
Geosphere	Low flow in repository parts

Table 7-14. Safety functions that are not maintained in the less probable scenario "High concentrations of complexing agents".

Component	Safety function
Chemical barriers	Good sorption

Cellulose degradation in the alkaline cement pore water gives rise to different degradation products. Of these, α-isosaccharinic acid (ISA) is both a strong complexing agent and one of the main degradation products. Cellulose degradation in an alkaline environment can therefore lead to reduced radionuclide retention in the concrete matrix. But the process takes place very slowly at the temperatures that prevail in SFR 1, and laboratory studies have only been conducted for a few decades, which means that there are no clear scientific results that can be used to predict how rapidly cellulose degradation can occur in SFR 1. Two extreme scenarios for cellulose degradation can be imagined. If, on the one hand, cellulose degradation goes quickly, say within 2,000 years, the increased radionuclide releases during this period would end up in the Baltic Sea (see Chapter 6). If, on the other hand, cellulose degradation goes slowly, say during a period of 20,000 years, the increased radionuclide releases would take place to terrestrial or agrarian ecosystems, which will probably be inhabited.

In the main scenario, concentrations of ISA from a degradation of approximately 10% of the cellulose as calculated for SAFE have been used /Fanger et al. 2001/, in other words on average about 10^{-4} M, but up to 0.9 M inside a few waste types. No degradation or removal of ISA was assumed in the calculations /Fanger et al. 2001/. In this scenario, "High concentrations of complexing agents", Kd-values for radionuclide transport calculations are instead chosen that correspond to an ISA concentration of 0.01 M for the entire repository and for all periods. This should be an unrealistically pessimistic assumption. The quantities of cellulose in the entire repository are not great enough to give such high concentrations of ISA in all repository parts. In the case of the waste types where there is enough cellulose, the concentrations of ISA are much lower just after repository closure, since the cellulose has not yet had time to degrade. Even if rapid cellulose degradation is assumed, equivalent to e.g. 10% in 2,000 years, this degradation would proceed gradually. Further ahead in time, the degradation of the concrete barriers due to e.g. permafrost will lead to some dilution of ISA.

In summary, it can be concluded that the scenario is highly pessimistic. The probability that it would occur is nevertheless set at 0.1 in order to guard against unknown processes of degradation of plastics and cellulose that could take place during long periods of time.

7.6.6 Gas-driven advection

The gas-driven advection case is based on the fact that gas generated in the repository due to corrosion and microbial processes gives an advective flow that drives out contaminated water to other parts of the system than in a situation with no gas.

The probability of this scenario is difficult to quantify, but is deemed to be less than one. The scenario must therefore be included in the final summation of risk.

7.6.7 Wells

According to government regulations, future scenarios and events that can affect the long-term safety of can affect should be based on present-day conditions and habits. The possibility can therefore not be ruled out that man will, like today, drill for both water and geothermal heat or perform certain types of geological investigations that lead to inadvertent intrusion in the repository and will thereby come into contact with the waste. This is dealt with, for example, in SR-Can as a part of the scenario category "Human actions", but for the much more shallow SFR 1, where wells in and around the repository are a part of the reference evolution, this is handled in a separate scenario that is added to the main scenario in the final summation of risk. The scenario "Wells" is based on the assumption that the safety function "No wells" cannot be maintained, Table 7-16.

Table 7-15. Safety functions that are not maintained in the less probable scenario "Gas-driven advection".

Component	Safety function
Engineered barriers	Limit advective transport

Table 7-16. Safety functions that are not maintained in the less probable scenario "Wells".

Component	Safety function
Biosphere	No wells

Scenario description

The reason for drilling may be a need for water and heating, or information on geological conditions. However, the repository has been located so that the probability of intrusion is very low, especially during the first thousand years before land uplift has left the rock above the repository high and dry. In the case of drilling for water, it is conceivable that this time is even longer, which has proved to be the case for wells in the Forsmark area, most of which have been drilled 1,000 years after the shoreline has passed. It is, however, possible to drill under water, which is done routinely today to explore oil deposits or study other geological conditions. The geological investigations that were done before the siting of SFR 1 did not reveal any geological indications for such prospecting.

Intrusion well in the repository

Boreholes drilled for geothermal heat according to current technology are relatively deep, usually more than 100 m and often closer to 200 metres, which means such a hole would go straight through the repository. It is likely that the change in the drilled material would be noticed by those doing the drilling. In such a case it is possible that some of the waste could be brought up to the ground surface via drill cuttings. That quantity is small, however, and could, if the diameter of the borehole is 1.5 dm and the height of the silo is 70 m (see Chapter 4), amount to 1.5 m^3. If the activity in the silo repository, with a diameter of 30 m (see Chapter 4), is assumed to be evenly distributed, $2.5 \cdot 10^{-5}$ of activity in the silo could be brought up. Normal practice when drilling geothermal wells is that the drill cuttings are collected in large containers for transport to a landfill, where they are used as cover material. The material can also be used as construction material for building ski hills, for example. The radionuclides can then slowly leach out to areas from which food for man and animals may be taken. The exposure is, however, likely to be much lower than for a pessimistically assumed well straight down into the repository, see below. The probability of such well intrusions is also low. The probability can be estimated by multiplying the well frequency (about 0.5 per km^2, see section 6.3.2) by the area of each repository part. The probability of intrusion wells in the silo is thereby found to be about $4 \cdot 10^{-4}$ for the silo (top area about 800 m^2 and about $1.5 \cdot 10^{-3}$ for the rock vaults (top area about 3,000 m^2).

Well in discharge area

If a drinking water well is drilled directly down into the repository, man can come into direct contact with waste by consumption of the contaminated water which, due to limited dilution, may have relatively high radionuclide concentrations. However, wells with poor yields are not utilized. According to the well archive, most wells in the Forsmark area have good well yields, providing relatively high dilution, see further section 8.4.11 where the calculation case is presented.

To calculate the risk contribution for these consequences, it is necessary to take into account the probability that the well is located so that it is affected by the release from the repository. This probability can be calculated by multiplying the frequency of wells per unit surface area in the area by the surface area of the area through which the well must be drilled to be affected by the release.

The well frequency is estimated from an inventory wells in the area today /Kautsky 2001/. The expected well frequency in the area can be estimated to be about 0.5 well per km^2. The analysis of dilution in wells (see section 6.5.2) shows that a well can only be significantly affected if it is located immediately adjacent to the discharge area. The size of the discharge area is less than 0.2 km^2 (see Figure 6-9).

In other words, the probability that there will be a well located within the area where it can be significantly affected is lower than 0.1.

7.6.8 Alternative inventory

The radionuclide inventory that is assumed to be valid for SAR-08 is a reference inventory arrived at in 2007 /Almkvist and Gordon 2007/. A radionuclide inventory without uncertainties, presented in Table 8.1, is used in the main scenario.

As an alternative to the inventory used in the main scenario, where the uncertainties are assumed to be symmetrically distributed around the mean inventory presented in Table 8-5, the inventory used in this residual scenario is one where the total activity has been scaled up (described in section 7.5.1) so that it corresponds to the maximum licensed activity. This new inventory has an activity that is about seven times greater than the mean activity in the main scenario and would, if today's packaging were used, have a greater volume than is available in SFR 1.

The residual scenario "Alternative inventory" is instead intended to study the radiological risk of filling the repository to the maximum licensed activity without taking into account the probability of this. The scenario is also used to provide a picture of the influence of the correlation factors on the radiological risk.

7.6.9 Loss of barrier function, near-field I and II

The residual scenario is based on loss of barrier function in accordance with the regulations' third scenario category, residual scenarios. The following two cases are selected for further analysis:

I. The main scenario's Weichselian variant, but sorption in the near-field is excluded.

II. The main scenario's Weichselian variant, but the barrier function in the silo and BMA repositories is excluded.

Table 7-17. Safety functions that are not maintained in the residual scenario "Alternative inventory".

Component	Safety function
Limited quantity of activity	Activity in repository part

7.6.10 Loss of barrier function, far-field

The residual scenario is based on loss of barrier function in accordance with the regulations' third scenario category, residual scenarios. The following case is selected for further analysis:

I. The main scenario's Weichselian variant, but without transport-limiting properties in the geosphere, in other words it is assumed that the near-field releases from the main scenario's Weichselian variant reach the biosphere directly.

7.6.11 Abandoned unclosed repository

The previously described scenarios, where the long-term evolution of the repository has been analyzed, are supplemented with a case where the radiological effects of an abandoned unclosed repository are studied. No radiological risk is presented for this residual scenario; the scenario is studied without its probability being assessed in accordance with SKIFS 2002:1.

In this residual scenario, it is assumed that the repository is abandoned without being closed and sealed. This means that the pumping of groundwater that is performed continuously today (about 6 l/min) ceases and that the repository becomes filled with water within a relatively short time. If the same inflow of water continues, this means that the repository will be filled with water during a short period of tens of years (the fact that the boundary conditions that control the inflow will change is disregarded in these simplified calculations).

During normal operation of SFR 1, the waste is backfill-grouted continuously, which means that all waste will not be accessible at first. With time, however, concrete barriers and waste packaging will degrade and radionuclides will be released and dissolve in the water that has filled the repository. Since the sorption capacity that exists in the repository is expected to endure for a long time, the nuclides that are released will sorb to concrete, bentonite, the shotcrete in tunnels and to other materials in the various repository parts and the tunnel system. Nor is it unreasonable to assume that the bentonite that surrounds the silo repository will be dissolved in the water that fills the repository, which results in additional sorption capacity.

If SFR 1 is abandoned, it can be assumed that this will happen during the period when the repository is under water and that the release will take place to the Baltic Sea, where dilution is great. Since the regional hydrogeological flow is small in relation to the water volume present in the repository, however, it will take a long time to replace the water in the repository and transport it out into the Baltic Sea. In other words, the water volume in the repository will be the same for a long period of time and the radionuclides that are dissolved are expected to remain in the repository system.

Since the groundwater that is pumped out of the system today is relatively saline, it is not likely that the water volume that fills the repository will be used as a water supply as long as the repository is situated near the sea. On the other hand, it is not unreasonable to assume that the influx of meteoric water and limited remixing due to the difference in salinity and temperature could lead to the formation of a fresh water pool near the tunnel opening. Viewed over an extended period, fresh water could seep down into the repository and replace the saline water present there today with potable fresh water. As a result, a future population could conceivably consume contaminated water taken directly from the repository's opening. In order for water to be contaminated, however, the concrete that is present around and in the waste packages must no longer be functional. In the reference evolution it is assumed that this takes thousands of years, depending on the repository part. Based on these assumptions, a calculation case is presented for "Abandoned unclosed repository" in Chapter 8.

7.6.12 Compilation of selected scenarios

Based on previously derived alternative repository evolutions and the scenario descriptions presented in section 7.6, Table 7-18 summarizes the selected scenarios. The table also shows the scenario categories that are described in the beginning of section 7.3.

Table 7-18. Scenarios with probabilities and categories.

Scenarios	Section	Probability	Category
Weichselian variant	7.4.1		Main scenario
Greenhouse variant	7.4.2		
Earthquake	7.6.1	Table 7-10	Less probable scenarios
Early freezing of the repository	7.6.2	Less than 1	
Defective engineered barriers [1]	7.6.3	–	
Talik	7.6.4	Less than 1	
High concentrations of complexing agents	7.6.5	0.1	
Gas-driven advection	7.6.6	Less than 1	
Wells [2]	7.6.7	Intrusion well in rock vaults $1.5 \cdot 10^{-3}$ Intrusion well in silo $4 \cdot 10^{-4}$ Well in discharge area 0.1	
Alternative inventory	7.6.8	–	Residual scenarios
Loss of barrier function, near-field I	7.6.9	–	
Loss of barrier function, near-field II	7.6.9	–	
Loss of barrier function, far-field	7.6.10	–	
Abandoned unclosed repository	7.6.11	–	

[1] Presents only hydrogeological consequences and is not evaluated as a separate scenario.

[2] Refers to the probability that a well exists at a given time. Se further discussion of risk dilution in section 10.4.

7.6.13 Scenario combinations

The method used to arrive at scenarios in this chapter is based on analyzing for each safety function what events, processes or data uncertainties make it impossible for the safety function to be maintained. In this way, scenario-initiating events, processes or data uncertainties have been identified.

Besides the identified scenarios where each alternatives repository evolution is represented, it is also possible to imagine combinations of alternative repository evolutions and scenarios.

Certain scenario combinations will be impossible, however, since either causes or consequences may be mutually exclusive, while other combinations are possible and must be taken into consideration. To do this, data intervals and conceptual models must have been selected. These intervals and models are presented in Chapter 8 along with the scenario combinations considered relevant for further analysis.

8 Description of calculation cases

8.1 Introduction

This chapter presents the calculation cases for radionuclide transport that have been arrived at on the basis of the scenario analysis carried out in Chapter 7. Chapter 8 begins with a description of calculation codes, processing of data and how the problems have been modelled. This is followed by a presentation of the calculation cases, which refer to the scenarios that were selected for analysis in Chapter 7.

8.2 Calculation codes and processing of data

Transport and dose calculations have been carried out with two different software packages. Amber /Enviros and Quintessa 2007/ has been used for transport in the near- and far-field, while Pandora /Åstrand et al. 2005/ has been used for radionuclide transport calculations in the biosphere. Both programs divide the modelled area into a number of compartments and describe transport between the different compartments mathematically. The expressions that describe transport between compartments vary in different parts of the system. While transport in the near-field is mainly described in terms of diffusion and advection, transport in the biosphere can also be described in terms of more large-scale processes such as sedimentation or bioturbation (mixing of different soil layers by living organisms).

Equation 8-1 represents the system of differential equations that are solved by both Amber and Pandora. If the total amount of radionuclide *m* in compartment *i* is I_i^m (mol), then this can be expressed as

$$\frac{dI_i^m}{dt} = -\left[\lambda_r^m + \sum_j \lambda_{ij}\right] I_i^m + \lambda_r^{m+1} I_i^{m+1} + \sum_j \lambda_{ji} I_j^m \qquad (8\text{-}1)$$

In this system of equations, λ_{ij} is the exchange rate between compartment *i* and compartment *j* (y^{-1}), λ_r^{m+1} is the decay rate of parent nuclide *m+1* (y^{-1}), and λ_r^m is the decay rate of nuclide *m* (y^{-1}). Since these equations are linear, an initial doubling of the quantity of radionuclides will lead to a doubling of the quantity of radionuclides in other compartments as well, even for long times.

As is evident from equation 8-1, only an outward transport rate from a compartment is defined. By defining the corresponding outward transport in the receptor compartment, gradient-driven flows such as diffusion can be described. By defining maximum levels for I_i^m, concentration-limiting processes can be included in the models being studied, and by changing transport rates with time, different dynamic processes can be included in the types of problems that can be solved. The latter is normally done either by choosing a solver that permits this or by performing the calculations as a quasi-steady-state approximation, i.e. by dividing the simulated time into a number of steps and assuming steady-state conditions (λ_{ij} in equation 8-1 is kept constant) in each such time step.

8.2.1 Amber

Amber was developed by Enviros and Quintessa to handle radionuclide transport in SFR-like systems. According to Enviros, Amber is mainly used for safety assessment of nuclear facilities by a total of 59 organizations in 24 countries /Thompson et al. 2008b/.

Amber has a graphical user interface where the different compartments and the flow of different radionuclides between them are defined. Radionuclides are allowed to decay and daughter nuclides to be generated within each compartment. Amber handles dynamic changes in different states and an adaptive time-stepping permits modelling over the time scales that are relevant for the problem, even if transient elements occur.

Additional factors that make Amber a suitable code for the problem at hand is that the code can handle:

- Any number of compartments.
- Any number of radionuclides.
- Several different transport mechanisms between compartments.
- Sub-models that can be defined.
- Non-linear transport processes.
- Probabilistic calculations.

In an introductory study /Thompson et al. 2008b/, the models used for the safety assessment calculations in the SAFE project /SKB 2001c/ were implemented in Amber with good results. Since Nucflow, which was used in the SAFE project, and Amber both describe the problem with compartments, there is no conceptual difference between the two codes. Nevertheless, two different modelling concepts are assumed for transport in the geosphere. The semianalytical FARF31 code /Norman and Kjellbert 1990/ was used in the SAFE project, while SAR-08 uses a compartment-based model for this part of the system as well. Previous comparison has shown that there is little difference between these two modelling concepts /Maul et al. 2003/.

8.2.2 Pandora

Pandora /Åstrand et al. 2005/ is a plugin for Simulink (for more information see www.mathworks.com), developed to make it easier to develop and simulate box models for radionuclide transport.

When Pandora is run in Simulink, the modelling is done in a graphical environment, where each block fills a specific function. Besides the built-in blocks in Simulink (mathematical operators, signal processing etc), Pandora adds additional blocks, such as:

- Compartment.
- Different transfer functions (to specify the transfer rate between compartments).
- Radionuclide processor (to specify radionuclides and decay chains in the model).
- Conversion block between mole and Becquerel.
- Filter block (to select a subset of radionuclides).
- Result block (to generate graphs and export results to MS Excel).
- Parameter block.

Simulink permits a mixture of both continuous and discrete systems. This, together with the fact that Simulink is a flexible and relatively open development environment with a coupling to Matlab, makes Pandora well suited for development and simulation of complex systems. Pandora utilizes the built-in numerical solvers for ordinary differential equations in Simulink.

Pandora has been used with good results by both SKB and Posiva in the development of dynamic landscape models for calculating radionuclide transport in the biosphere in SR-Can /SKB 2006a/.

8.2.3 Eikos

Eikos /Ekström and Broed 2006/ is a tool for probabilistic calculations and uncertainty and sensitivity analysis of models developed in Matlab and Simulink (see www.mathworks.com for more information). Eikos is fully integrated with Pandora (see section 8.2.2).

Eikos includes the latest methods for sensitivity and uncertainty analysis, which can cope with linear, non-linear, as well as non-monotone dependencies between input data and output data for models.

Eikos Permits Monte Carlo simulations with standard sampling (Simple Random Sampling) or Latin Hypercube Sampling (LHS) and supports presentation of results in both numerical and graphical form. Since Eikos is fully integrated with Pandora, sensitivity analysis and uncertainty analysis can easily be performed on models developed in Pandora. Models developed in Pandora can be opened directly in Eikos, and all parameters and simulation results are listed in the Eikos user interface .

Eikos has been compared and tested against @Risk (see www.palisade.com for more information), which is a well-established commercial tool, and against test functions that have exact analytical solutions /Ekström 2005/. These tests have shown that Eikos generates reliable results.

8.2.4 Input data for calculations

The radionuclides to be included in the calculations are determined on the basis of the inventory and mobility of the radionuclides /Thomson et al. 2008a/ and are presented in Table 8-1. Input data for the calculations of radionuclide transport in the near- and far-field are presented together with these calculations in a background report /Thomson et al. 2008a/. Dose calculations are presented in a special report /Bergström et al. 2008/.

The radionuclides that have been used and their half-lives are presented in Table 8-1. Decay products have not been included, with the exception of Mo-93 with its decay daughter Nb-93m. C-14 occurs both organic and inorganic carbon, where both forms have identical half-lives.

8.2.5 Transfer of data between models

Near- and far-field simulations are performed in the same system and no data are sent outside the Amber environment. Results of calculations of the far-field are transferred to the biosphere transport calculations as text files.

8.2.6 Incremental changes, quasi-steady-state simulations and transient behaviour

Input data to radionuclide transport calculations come from a number of different sources. Different types of material data, for example for sorption to bentonite, are obtained from laboratory tests and adapted to existing groundwater compositions /Ochs and Talerico 2004/. Site-specific diffusivities are based on results of site investigations performed in Forsmark and in Laxemar, while certain data, for example concerning hydrogeological conditions, have been obtained by carrying out simulations based on site-specific information.

Since it is impossible (or at least impractical) to perform all simulations in one and the same code with the same requirements on accuracy and resolution in time, the problem will inevitably arise that different codes deliver results at different times and for different spatial locations. Since results from one code are used as input data in other calculations, it is necessary to interpolate data. This is particularly important in order to solve problems that extend over such long times that it is necessary to use a solver that adapts the time steps according to results and input data.

Table 8-1. Half-lives in the radionuclide transport calculations /Thomson et al. 2008a/ and radionuclide inventory /Almkvist and Gordon 2007/ used in SAR-08.

Nuclide	Half-life (years)	Total (Bq)	Silo (Bq)	BMA (Bq)	1 BTF (Bq)	2 BTF (Bq)	BLA (Bq)
H-3	$1.23 \cdot 10^{1}$	$3.9 \cdot 10^{10}$	$3.5 \cdot 10^{10}$	$3.8 \cdot 10^{9}$	$1.6 \cdot 10^{8}$	$4.0 \cdot 10^{8}$	$2.2 \cdot 10^{7}$
C-14 org. [1]	$5.73 \cdot 10^{3}$	$1.8 \cdot 10^{12}$	$1.4 \cdot 10^{12}$	$3.2 \cdot 10^{11}$	$7.4 \cdot 10^{9}$	$5.5 \cdot 10^{10}$	$1.2 \cdot 10^{9}$
C-14 inorg. [1]	$5.73 \cdot 10^{3}$	$4.1 \cdot 10^{12}$	$3.2 \cdot 10^{12}$	$7.4 \cdot 10^{11}$	$1.7 \cdot 10^{10}$	$1.3 \cdot 10^{11}$	$2.7 \cdot 10^{9}$
Cl-36	$3.01 \cdot 10^{5}$	$1.4 \cdot 10^{9}$	$1.1 \cdot 10^{9}$	$2.3 \cdot 10^{8}$	$1.1 \cdot 10^{7}$	$3.1 \cdot 10^{7}$	$1.0 \cdot 10^{6}$
Ni-59	$7.60 \cdot 10^{4}$	$9.5 \cdot 10^{12}$	$7.3 \cdot 10^{12}$	$2.1 \cdot 10^{12}$	$2.1 \cdot 10^{10}$	$4.2 \cdot 10^{10}$	$5.3 \cdot 10^{9}$
Co-60	5.27	$9.3 \cdot 10^{13}$	$8.5 \cdot 10^{13}$	$7.0 \cdot 10^{12}$	$2.9 \cdot 10^{11}$	$3.7 \cdot 10^{11}$	$3.6 \cdot 10^{10}$
Ni-63	$1.00 \cdot 10^{2}$	$1.2 \cdot 10^{15}$	$8.9 \cdot 10^{14}$	$2.6 \cdot 10^{14}$	$2.3 \cdot 10^{12}$	$2.8 \cdot 10^{12}$	$6.6 \cdot 10^{11}$
Se-79	$1.13 \cdot 10^{6}$	$1.3 \cdot 10^{9}$	$1.0 \cdot 10^{9}$	$2.1 \cdot 10^{8}$	$5.9 \cdot 10^{6}$	$2.4 \cdot 10^{7}$	$4.9 \cdot 10^{5}$
Sr-90	$2.88 \cdot 10^{1}$	$1.3 \cdot 10^{13}$	$1.1 \cdot 10^{13}$	$1.7 \cdot 10^{12}$	$6.4 \cdot 10^{10}$	$2.1 \cdot 10^{11}$	$4.7 \cdot 10^{9}$
Mo-93	$4.00 \cdot 10^{3}$	$3.7 \cdot 10^{9}$	$2.9 \cdot 10^{9}$	$6.8 \cdot 10^{8}$	$4.4 \cdot 10^{7}$	$8.9 \cdot 10^{7}$	$2.0 \cdot 10^{7}$
Nb-94	$2.03 \cdot 10^{4}$	$2.0 \cdot 10^{10}$	$1.6 \cdot 10^{10}$	$3.6 \cdot 10^{9}$	$8.5 \cdot 10^{7}$	$4.2 \cdot 10^{8}$	$1.3 \cdot 10^{7}$
Tc-99	$2.11 \cdot 10^{5}$	$4.1 \cdot 10^{11}$	$3.6 \cdot 10^{11}$	$3.7 \cdot 10^{10}$	$7.0 \cdot 10^{9}$	$7.6 \cdot 10^{9}$	$5.0 \cdot 10^{8}$
Ag-108m	$4.18 \cdot 10^{2}$	$1.2 \cdot 10^{11}$	$9.2 \cdot 10^{10}$	$2.0 \cdot 10^{10}$	$4.8 \cdot 10^{8}$	$2.3 \cdot 10^{9}$	$4.2 \cdot 10^{8}$
Sn-126	$1.00 \cdot 10^{5}$	$1.6 \cdot 10^{8}$	$1.3 \cdot 10^{8}$	$2.7 \cdot 10^{7}$	$7.4 \cdot 10^{5}$	$2.9 \cdot 10^{6}$	$6.2 \cdot 10^{4}$
I-129	$1.57 \cdot 10^{7}$	$1.0 \cdot 10^{9}$	$8.1 \cdot 10^{8}$	$1.8 \cdot 10^{8}$	$3.1 \cdot 10^{6}$	$1.9 \cdot 10^{7}$	$3.1 \cdot 10^{5}$
Cs-135	$2.30 \cdot 10^{6}$	$5.1 \cdot 10^{9}$	$4.0 \cdot 10^{9}$	$1.0 \cdot 10^{9}$	$1.6 \cdot 10^{7}$	$1.1 \cdot 10^{8}$	$2.0 \cdot 10^{6}$
Cs-137	$3.01 \cdot 10^{1}$	$1.3 \cdot 10^{14}$	$1.1 \cdot 10^{14}$	$2.0 \cdot 10^{13}$	$6.7 \cdot 10^{11}$	$1.8 \cdot 10^{12}$	$4.8 \cdot 10^{10}$
Ho-166m	$1.20 \cdot 10^{3}$	$8.9 \cdot 10^{9}$	$7.0 \cdot 10^{9}$	$1.6 \cdot 10^{9}$	$5.8 \cdot 10^{7}$	$1.9 \cdot 10^{8}$	$1.7 \cdot 10^{7}$
Np-237	$8.77 \cdot 10^{1}$	$1.6 \cdot 10^{8}$	$1.3 \cdot 10^{8}$	$2.5 \cdot 10^{7}$	$4.1 \cdot 10^{5}$	$1.9 \cdot 10^{6}$	$2.7 \cdot 10^{4}$
Pu-239	$2.41 \cdot 10^{4}$	$1.1 \cdot 10^{10}$	$8.9 \cdot 10^{9}$	$2.0 \cdot 10^{9}$	$1.5 \cdot 10^{8}$	$2.0 \cdot 10^{8}$	$1.3 \cdot 10^{7}$
Pu-240[2]	$6.56 \cdot 10^{3}$	$2.3 \cdot 10^{10}$	$1.8 \cdot 10^{10}$	$4.0 \cdot 10^{9}$	$3.0 \cdot 10^{8}$	$4.0 \cdot 10^{8}$	$2.6 \cdot 10^{7}$
Am-241[3]	$4.32 \cdot 10^{2}$	$5.0 \cdot 10^{11}$	$4.9 \cdot 10^{11}$	$6.9 \cdot 10^{9}$	$8.4 \cdot 10^{8}$	$4.9 \cdot 10^{8}$	$5.0 \cdot 10^{7}$
Pu-241[3]	$1.44 \cdot 10^{1}$	$8.3 \cdot 10^{11}$	$6.8 \cdot 10^{11}$	$1.3 \cdot 10^{11}$	$6.4 \cdot 10^{9}$	$7.0 \cdot 10^{9}$	$3.6 \cdot 10^{8}$
Pu-242	$3.73 \cdot 10^{5}$	$1.1 \cdot 10^{8}$	$7.9 \cdot 10^{7}$	$2.3 \cdot 10^{7}$	$1.5 \cdot 10^{6}$	$1.6 \cdot 10^{6}$	$9.0 \cdot 10^{4}$
Am-243	$7.37 \cdot 10^{3}$	$1.1 \cdot 10^{9}$	$8.4 \cdot 10^{8}$	$2.3 \cdot 10^{8}$	$1.5 \cdot 10^{7}$	$1.6 \cdot 10^{7}$	$9.0 \cdot 10^{5}$
Cm-244[2]	$1.81 \cdot 10^{1}$	$1.1 \cdot 10^{10}$	$9.2 \cdot 10^{9}$	$1.2 \cdot 10^{9}$	$8.3 \cdot 10^{7}$	$9.0 \cdot 10^{7}$	$1.9 \cdot 10^{7}$

[1] Organic and inorganic C-14 are analyzed separately due to different transport properties.

[2] The inventory of individual nuclides is shown in the table, but in the calculations the inventory of Cm-244 is added to the inventory of Pu-240

[3] The inventory of individual nuclides is shown in the table, but in the calculations the inventory of Pu-241 is added to the inventory of Am-241.

The hydrogeological simulations in SAR-08 are based on simulations carried out by letting all input data to the model at that particular time be constant. By then combining results from the different times, results are obtained as a function of time. The resolution of the results in time will then be dependent on how closely-spaced the different times are in the underlying simulation.

In the case of a transport problem, rapid changes in input data will be visible as equally rapid changes in the radionuclide release. It is worth noting that when calculation results change quickly, this is a sign that the system reaches equilibrium quickly and that equally rapid changes in the results would not occur if the input data had changed continuously.

In the following text, there will be no further discussion in cases where peak values occur in results due to equally rapid changes in input data (for example changes in flow or change of biosphere object).

8.3 Conceptualization and spatial discretization of the different repository parts

Model discretization is described in the background report that describes the calculations /Thomson et al. 2008b/. Below is a description of each model followed by a short summary of the selected discretization.

8.3.1 Silo repository

Figure 8-1 shows the conceptual model that has been used to describe the silo repository. In the model, the internal parts of the silo have been divided into two radial sections, with bitumen-conditioned waste in the inner section and cement-conditioned waste in the outer section. In height the silo is divided into three vertical sections. The model includes three different types of waste: cement-conditioned waste in steel or concrete containers, and bitumen-conditioned waste in steel containers. Figure 8-1 shows, besides the waste, the different components that are modelled and the transport mechanisms that are assumed to dominate between the different components.

Based on the conceptual model shown in Figure 8-1, a discretized model was created (Figure 8-2) consisting of a total of 94 compartments where waste, sand and gravel above the silo, the sand and bentonite mixture above and below the silo, bentonite buffer around the silo, and different forms of concrete are represented /Lindgren et al. 2001, Thomson et al. 2008b/.

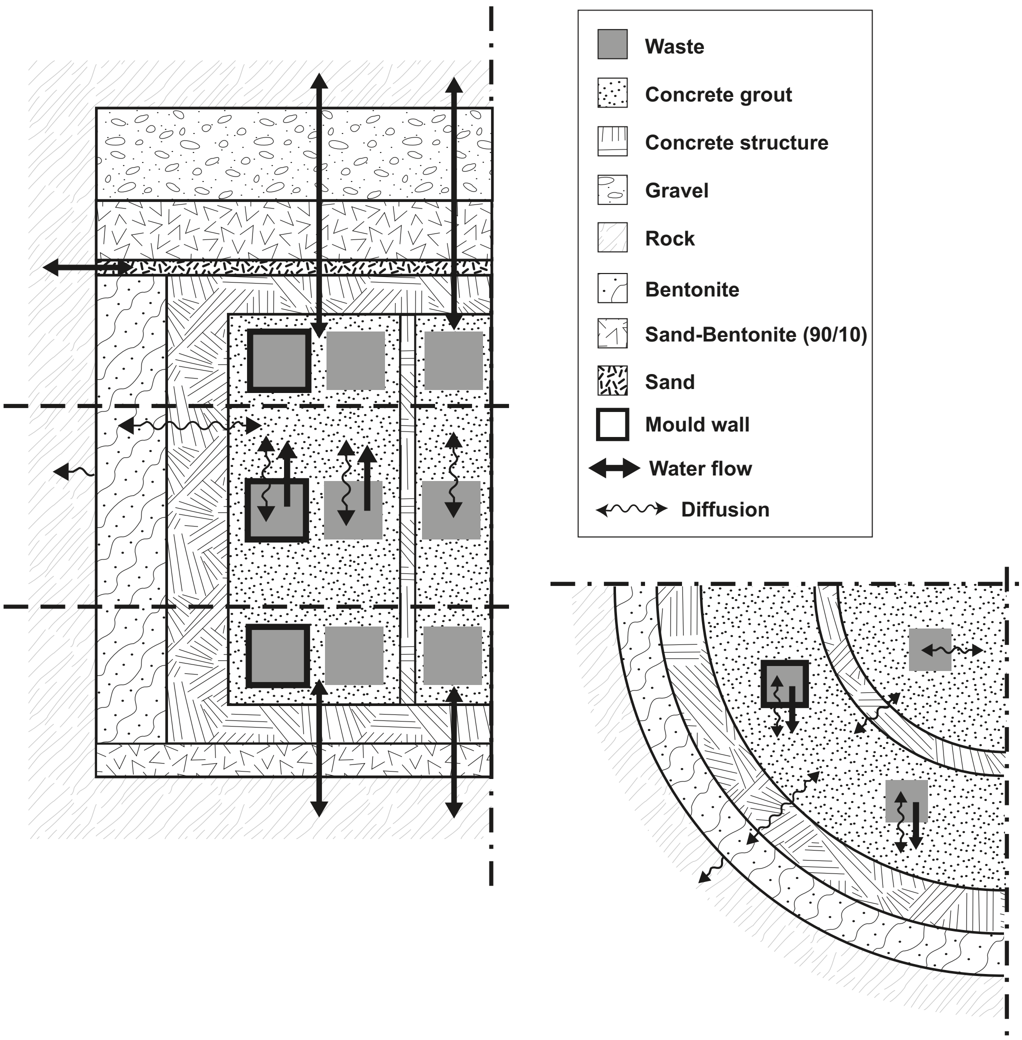


Figure 8-1. *Conceptual model of the silo repository, viewed from the side (left-hand figure) and from above (right) /Lindgren et al. 2001/.*

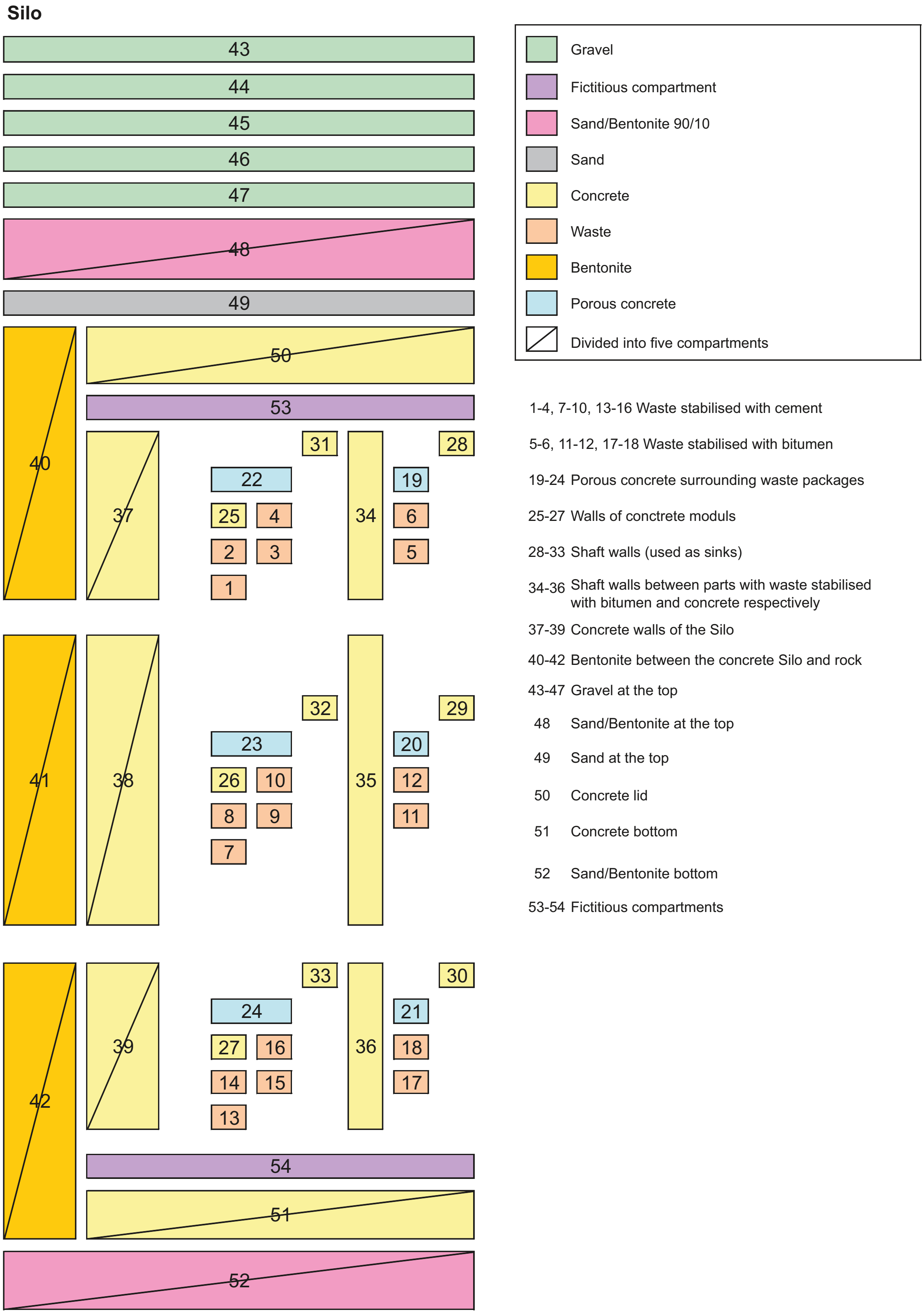
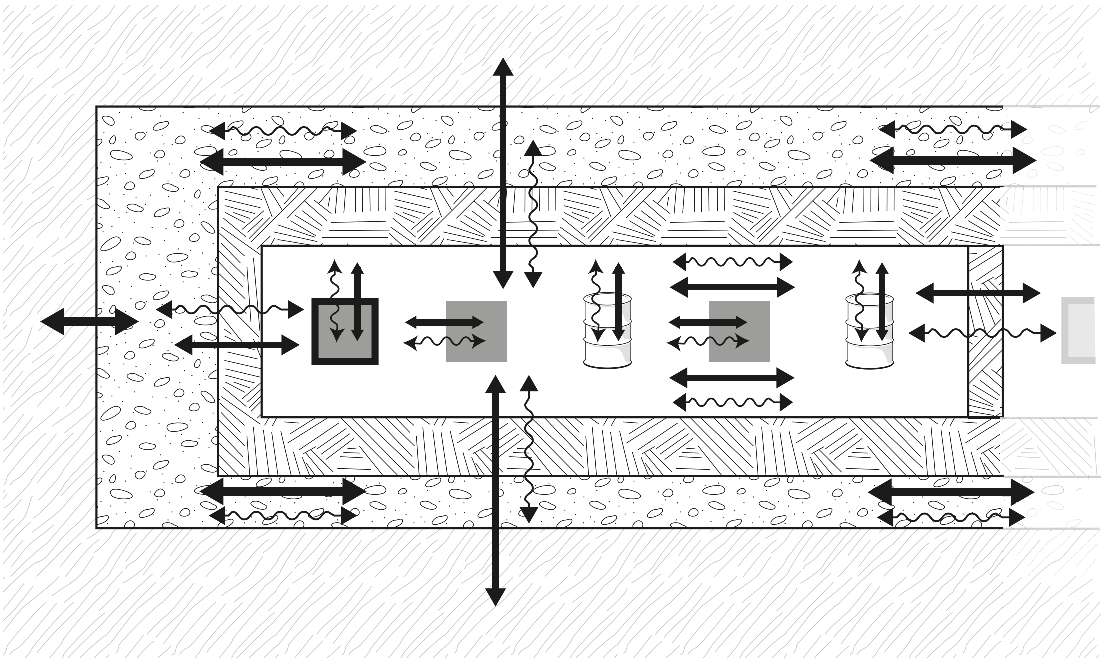


Figure 8-2. *Discretization of the silo repository in the Amber model. The different colours represent the different materials included in the model /Lindgren et al. 2001/.*

8.3.2 BMA repository

Figure 8-3 shows the conceptual model used to describe the BMA repository. The BMA repository consists of five sections where waste is stored and where all sections are surrounded by a gravel backfill with relatively high conductivity. Radionuclide transport between the different sections and the surrounding rock is assumed to take place both advectively and diffusively. It is assumed in the model that five different types of waste are stored in the BMA repository: concrete containers with cement-conditioned waste, steel containers with cement- or bitumen-conditioned waste and steel drums with cement- or bitumen-conditioned waste. The same diffusivity and sorption data is assumed to apply to the cement-conditioned waste types as to shotcrete.

Based on the conceptual model shown in Figure 8-3, a discretized model was created (Figure 8-4) consisting of a total of 161 compartments where waste, sorbing concrete and the conductive gravel backfill around the waste packages are represented /Lindgren et al. 2001, Thomson et al. 2008b/.



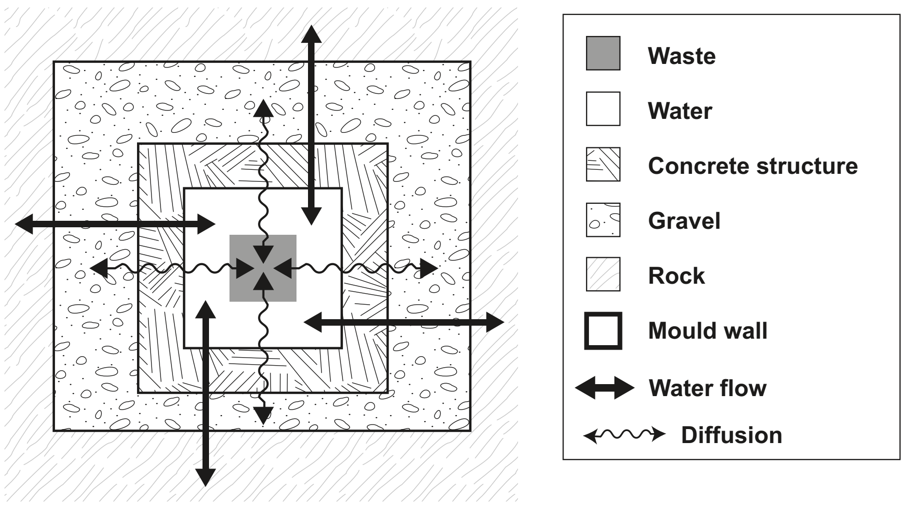
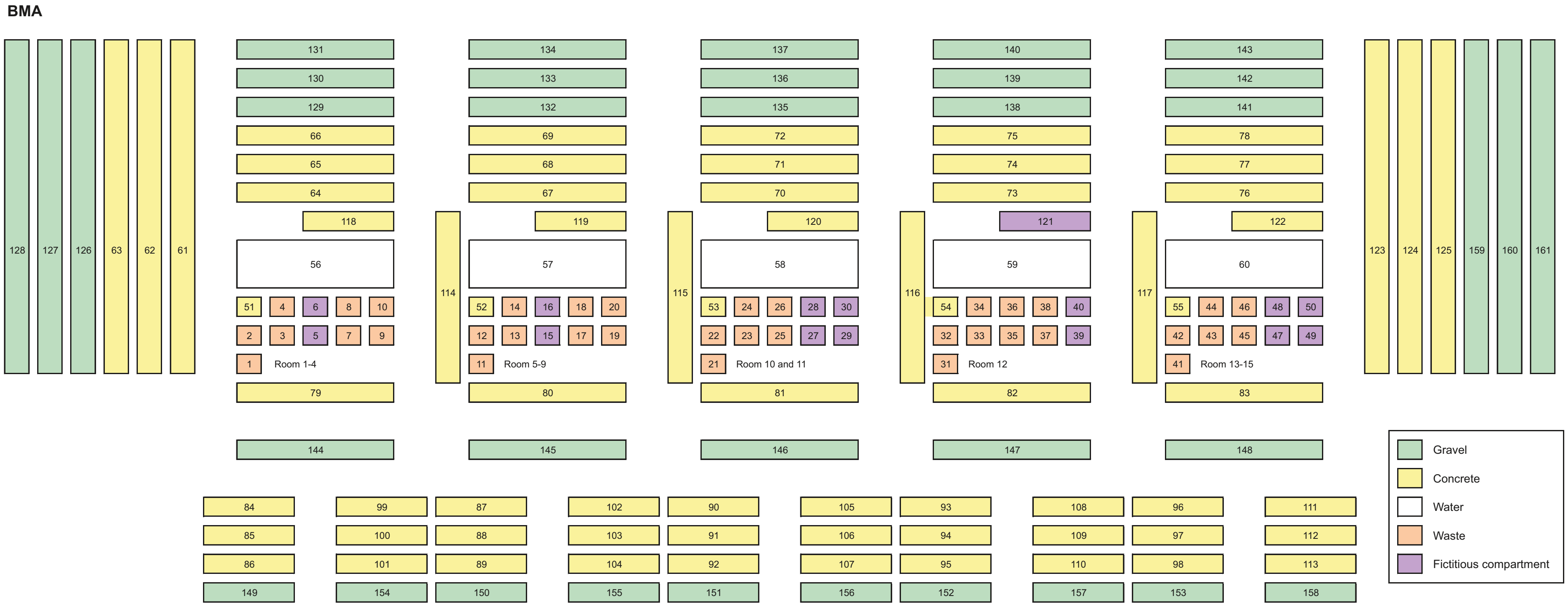


Figure 8-3. *Conceptual model of the BMA repository, viewed from the long side (upper figure) and the short side (lower) /Lindgren et al. 2001/.*



1-2, 11-12, 21-22, 31-32, 41-42	Waste stabilised with cement in concrete moduls
3-4, 13-14, 23-24, 33-34, 43-44	Waste stabilised with cement in steel containers
25-26, 35-36, 45-46	Waste stabilised with cement in steel drums
7-8, 17-18, 37-38	Waste stabilised with bitumen in steel containers
9-10, 19-20	Waste stabilised with bitumen in steel drums
5-6, 15-16, 27-30, 39-40, 47-50	Fictitious source terms
51-55	Walls of concrete moduls
56-60	Water inside encapsulation
61-63	Wall at short side of the structure (passage)
64-78	Ceiling of the structure
79-83	Bottom of the structure
84-98	Wall on left side of the structure
99-113	Wall on right side of the structure
114	Inner wall between room 4 and 5
115	Inner wall between room 9 and 10
116	Inner wall between room 11 and 12
117	Inner wall between room 12 and 13
118	Inner wall between room 1 and 2, 2 and 3, 3 and 4 (sink)
119	Inner wall between room 5 and 6, 6 and 7, 7 and 8, 8 and 9 (sink)
120	Inner wall between room 10 and 11 (sink)
121	Fictitious compartment (no inner wall, only one room)
122	Inner wall between room 13 and 14/15 and between room 14 and 15 (sink)
123-125	Wall at short side of the structure (loading zone)
126-128	Gravel at the end of the tunnel (passage)
129-143	Gravel at the top of the tunnel
144-148	Gravel at the bottom of the tunnel
149-153	Lateral gravel on the left side of the tunnel
154-158	Lateral gravel on the right side of the tunnel
159-161	Gravel at the end of the tunnel (loading zone)

Figure 8-4. *Discretization of the BMA repository in the Amber model. The different colours represent the different materials included in the model /Lindgren et al. 2001/.*

8.3.3 1BTF repository

Waste is stored in the 1BTF repository in drums, in concrete containers and in different types of steel containers. The drums are placed in compartments that hold 1,000 drums and are separated by concrete structures. Figure 8-5 shows how the different waste types are placed in 1BTF and how many drums can be held by each of the six compartments. Figure 8-6 shows how 1BTF is regarded conceptually. Since each compartment is backfilled with concrete grout, sorbing concrete will surround each waste drum. The waste in the BTF repository is surrounded by a conductive gravel backfill, but the difference in conductivity between the waste packages and the backfill is small, which means that advective transport in the waste packages cannot be disregarded.

Based on the conceptual model shown in Figure 8-6, a discretized model was created (Figure 8-7) consisting of a total of 195 compartments where waste, sorbing concrete and the conductive gravel backfill around the waste packages are represented /Lindgren et al. 2001, Thomson et al. 2008b/.

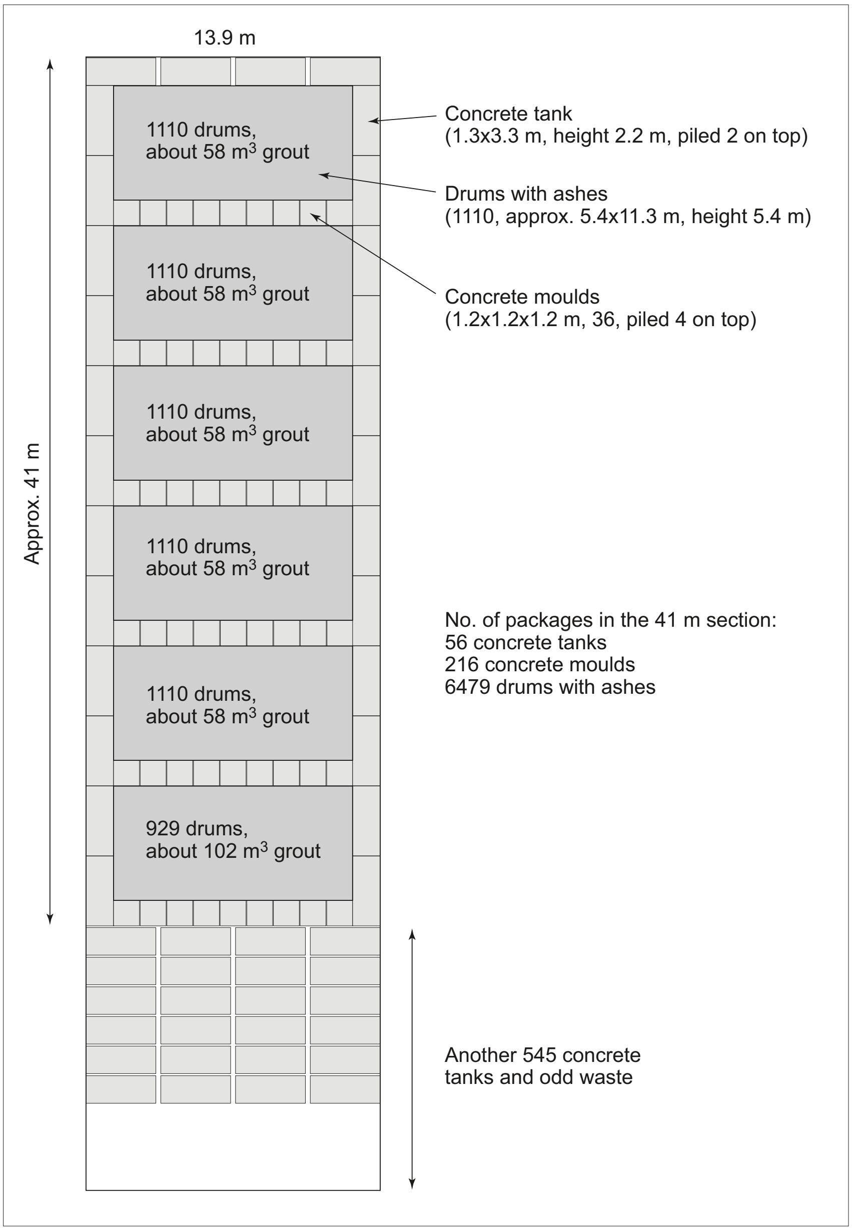


Figure 8-5. Waste components in the 1BTF repository consisting of six compartments with drums and an area with concrete moulds and odd waste all surrounded by concrete tanks /Lindgren et al. 2001/.

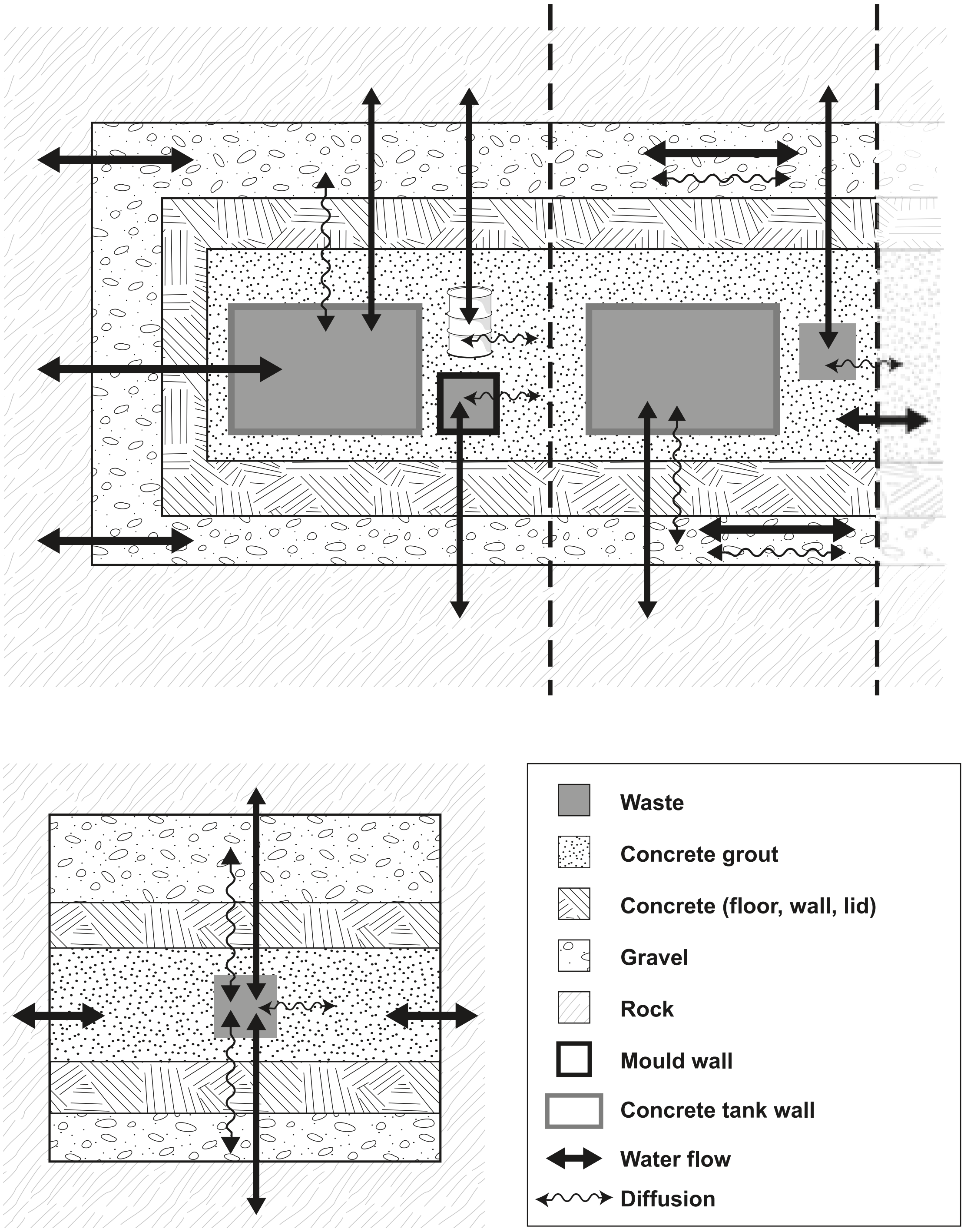


Figure 8-6. *Conceptual model of the 1BTF repository, viewed from the long side (upper figure) and the short side (lower) /Lindgren et al. 2001/.*

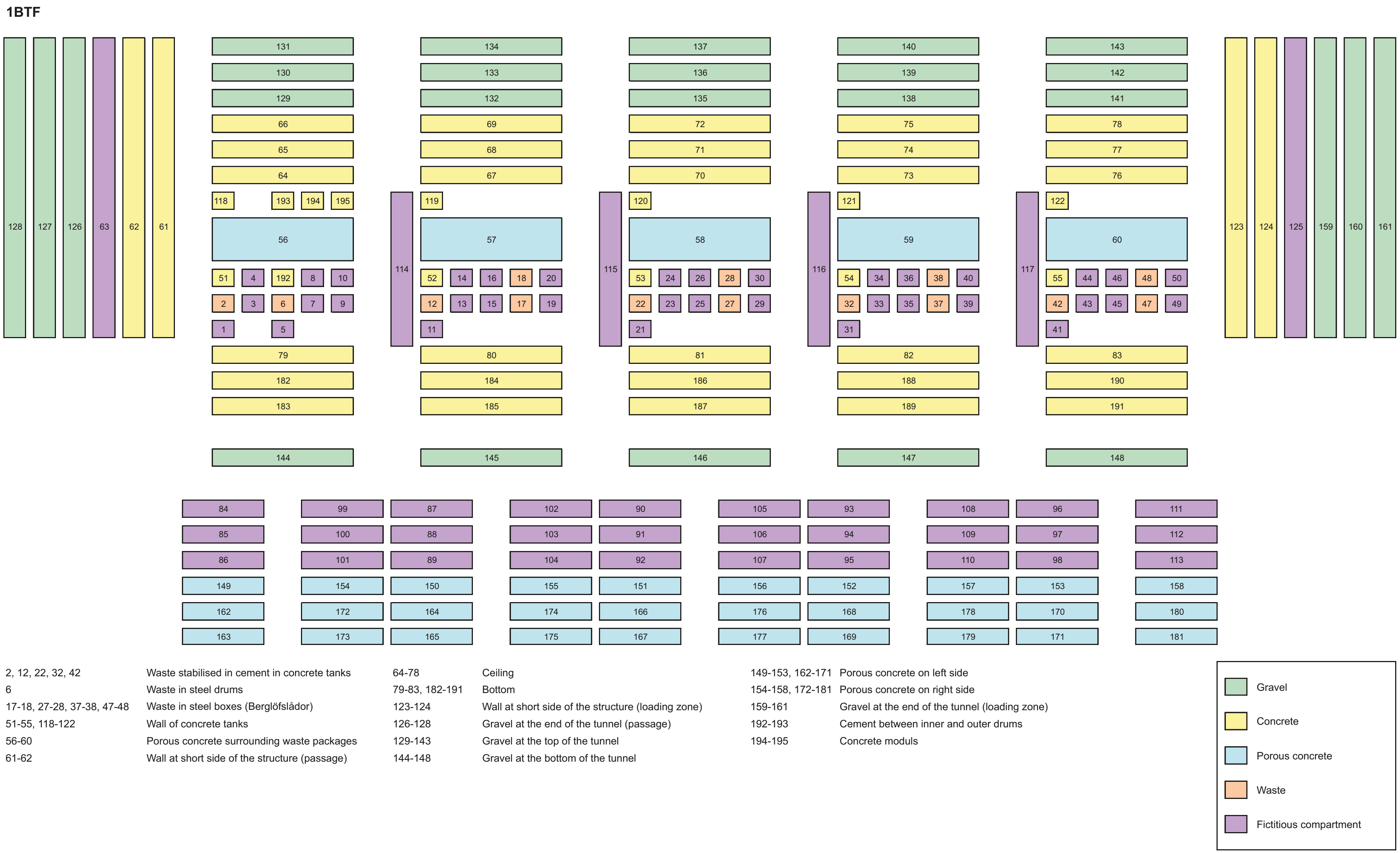


Figure 8-7. *Discretization of the 1BTF repository in the Amber model. The different colours represent the different materials included in the model.*

8.3.4 2BTF repository

The waste stored in the 2BTF repository consists mainly of ion exchange resins in concrete tanks. The conceptual model of 2BTF is presented in Figure 8-9. In the same way as in the 1BTF repository, the waste packages in the 2BTF repository are surrounded by a conductive gravel backfill, and in 2BTF as well the difference in conductivity between the waste packages and the backfill is small, which means that advective transport in the waste packages cannot be disregarded.

Based on the conceptual model shown in Figure 8-8, a discretized model was created (Figure 8-9) consisting of a total of 191 compartments /Lindgren et al. 2001, Thomson et al. 2008b/ where the waste packages, sorbing concrete and the conductive gravel backfill around the waste packages are represented.

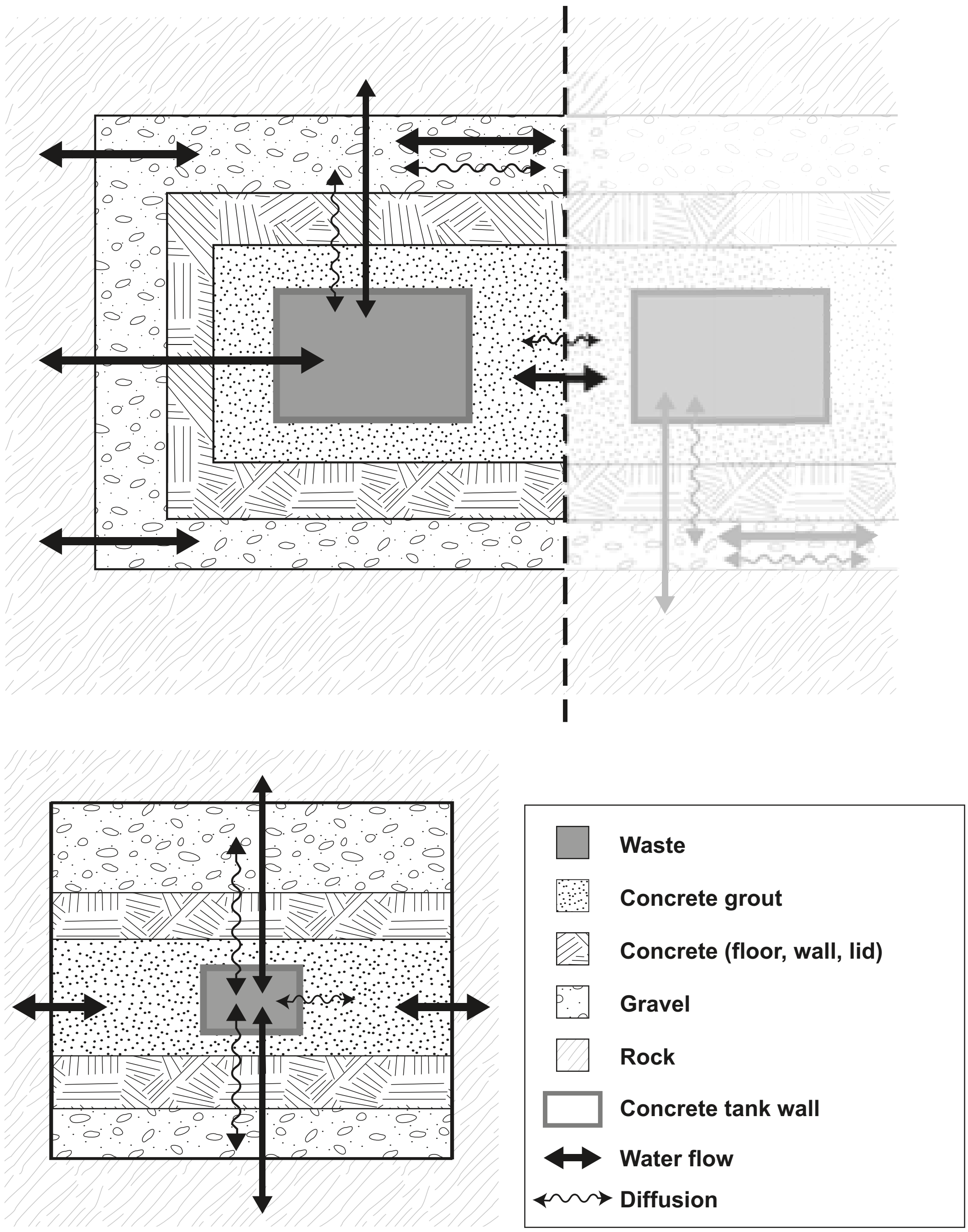


Figure 8-8. *Conceptual model of the 2BTF repository, viewed from the long side (upper figure) and the short side (lower) /Lindgren et al. 2001/.*

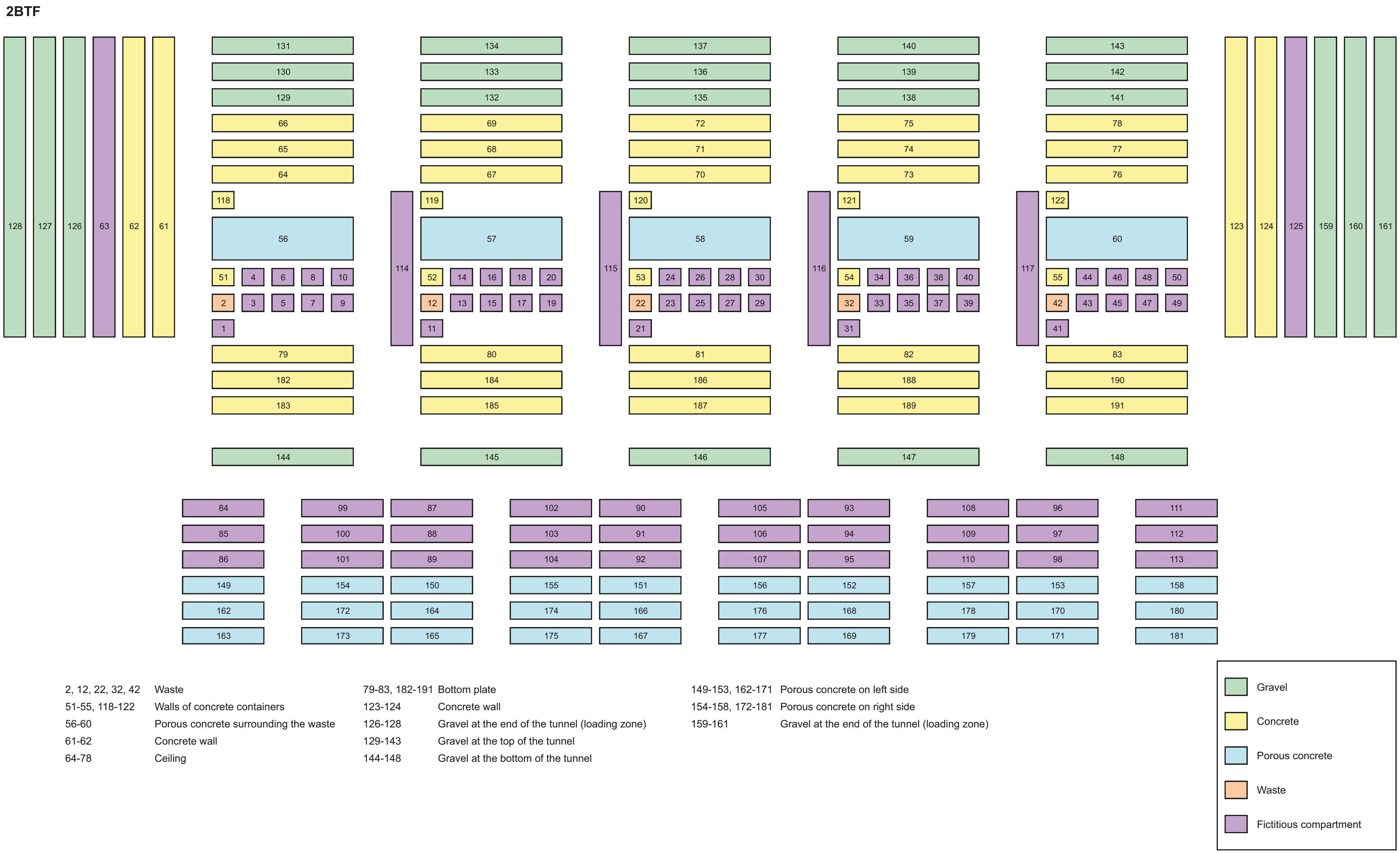


Figure 8-9. *Discretization of the 2BTF repository in the Amber model. The different colours represent the different materials included in the model /Lindgren et al. 2001/.*

8.3.5 BLA repository

In the BLA repository, it is assumed that no buffering material retards radionuclide transport; the repository is regarded conceptually as a number of sections that are totally intermixed by diffusive and advective transport between the sections, Figure 8-11. It is assumed that no sorption takes place and all compartments are in contact with the surrounding rock.

Based on the conceptual model shown in Figure 8-10, a discretized model was created (Figure 8-11) consisting of seven compartments /Lindgren et al. 2008, Thomson et al. 2008b/ where rock and the waste packages are represented.

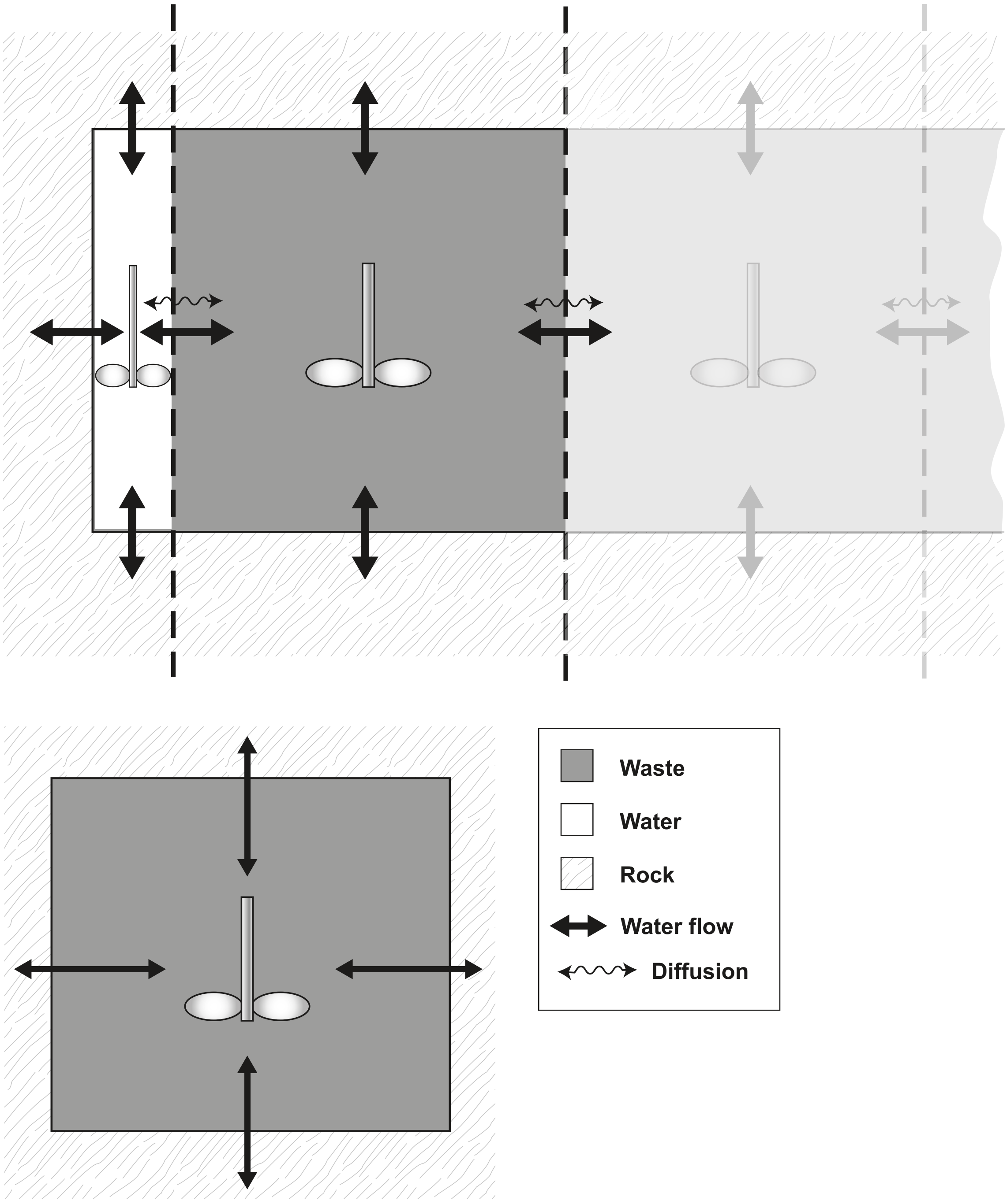
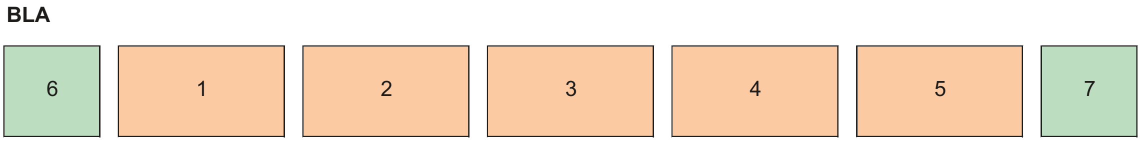


Figure 8-10. *Conceptual model of the BLA repository, viewed from the long side (upper figure) and the short side (lower); complete intermixing is assumed in each compartment (indicated by the stirrers) /Lindgren et al. 2001/.*



1–5 Source term
6–7 Gravel at the end of the rock vault

Figure 8-11. *Discretization of the BLA repository in the Amber model. The different colours represent the different materials included in the model /Lindgren et al. 2001/.*

8.3.6 Description of calculations in the near-field

Transport of radionuclides in the near-field is assumed to take place advectively or diffusively. The advective transport of radionuclide *m* from compartment *i* to *j*, $\lambda^{m}_{ij,adv}$ (y^{-1}), is described by the following equations

$$\lambda^{m}_{ij,adv} = \frac{Q_i}{Capacity^{m}_{i}} \qquad (8\text{-}2)$$

where

Q_i is the groundwater flux through compartment *i* (m^3/y)

$Capacity^{m}_{i}$ is the capacity of compartment *i* for radionuclide *m* (m^3) /Lindgren et al. 2001/

$$Capacity^{m}_{i} = V_i\left(\varepsilon_i + (1-\varepsilon_i)K^{m}_{i\,d}\rho_i\right) \qquad (8\text{-}3)$$

V_i is the volume of compartment *i* (m^3)

ε_i is the porosity of compartment *i* (–)

$K^{m}_{i\,d}$ is the sorption coefficient of radionuclide *m* in compartment *i* (m^3/kg)

ρ_i is the particle density (dry density) in compartment *i* (kg/m^3)

The availability of the radionuclides has been calculated as follows:

$$Avail^{m}_{i} = C^{m}_{i}\ Capacity^{m}_{i} \qquad (8\text{-}4)$$

where

$Avail^{m}_{i}$ is the amount of radionuclide *m* that is available for transfer in compartment *i* (mol)

C^{m}_{i} is the solubility for radionuclide *m* in compartment *i* (mol/m^3)

External advective flows from the near-field to the geosphere are also represented in the model according to 8-4.

The diffusive transport of radionuclide *m* from compartment *i* to *j*, $\lambda^{m}_{ij,diff}$ (y^{-1}), is described by the following equations

$$\lambda^{m}_{ij,diff} = \frac{1}{\tfrac{1}{2}\cdot\left(\mathrm{Res}^{k}_{i} + \mathrm{Res}^{k}_{j}\right)\cdot Capacity^{m}_{i}} \qquad (8\text{-}5)$$

where

Res^{k}_{i} is the diffusive transport resistance in compartment *i* in direction *k* (y/m^3)

Res^{k}_{j} is the diffusive transport resistance in compartment *j* in direction *k* (y/m^3)

For compartment *i,* the diffusive resistance in direction *k*, $\mathrm{Res}_\mathrm{i}^\mathrm{k}$, is given by

$$\mathrm{Res}_\mathrm{i}^\mathrm{k} = \frac{L_i^k}{A_i^k\, D_e^i} \tag{8-6}$$

L_i^k is the diffusion length in direction *l* for compartment *i* (m)

A_i^k is the cross-sectional area for diffusion perpendicular to direction *l* for compartment *i* (m^2)

D_e^i is the effective diffusion coefficient for compartment *i* (m^2/y)

In order to describe diffusion of radionuclides from the silo repository to the rock, an equivalent flow rate Q_{eq} (m^3/y) was used (described in the SAFE project's calculation report /Lindgren et al. 2001/).

The following are used for the geometric description of the different repositories:

- The volumes of the compartments, V_i, values for *L/A* (on *x*, *y* and *z* axes) and materials.
- The density, ρ_s, porosity, ε_i, and effective diffusivity, D_e , of the materials (as well as their sorption coefficient, K_d).
- Description of the diffusive transport resistances used between the compartments.
- Compartments through which the radionuclides leave the silo and the associated groundwater flux, *Q*.
- The equivalent flow rate Q_{eq} (m^3/y).

Certain parameters such as groundwater flux and sorption coefficient, K_d, vary with time.

8.3.7 Description of calculations in the geosphere

Based on how transport through fractured material is represented in Amber /Enviros and Quintessa 2007/, the geosphere has been described. The geosphere is represented as a two-dimensional array of compartments, see Figure 8-12. In the longitudinal dimension, the compartments (*F1*, *F2*, etc) are linked together to represent the advective flow paths along a fracture. The number of compartments in this dimension was set at 40 to reduce the effects of numerical dispersion on the simulation. The transversal dimension of compartments (*M1*, *M2*, etc) was included to represent parts of the adjacent rock where diffusive exchange takes place via matrix diffusion.

The advective transfer from compartment *i* to *j*, $\lambda_{ij,Adv}$ (y^{-1}), is described by the following equations /Thomson et al. 2008b/

$$\lambda_{ij,Adv} = \frac{v}{R_f L_i} \tag{8-7}$$

where

v is the groundwater velocity (m/y)

R_f is the effective retardation in the fracture (–)

L_i is the length of compartment *i* (m)

The inclusion of effective retardation in the fracture results from considering a thin layer of the matrix, which gives

$$R_f = 1 + a_w d_0 \theta R_m \tag{8-8}$$

where

a_w is the flow-wetted surface area (m^2/m^3)

d_0 is the thickness of the thin layer (m)

θ is the matrix porosity (–)

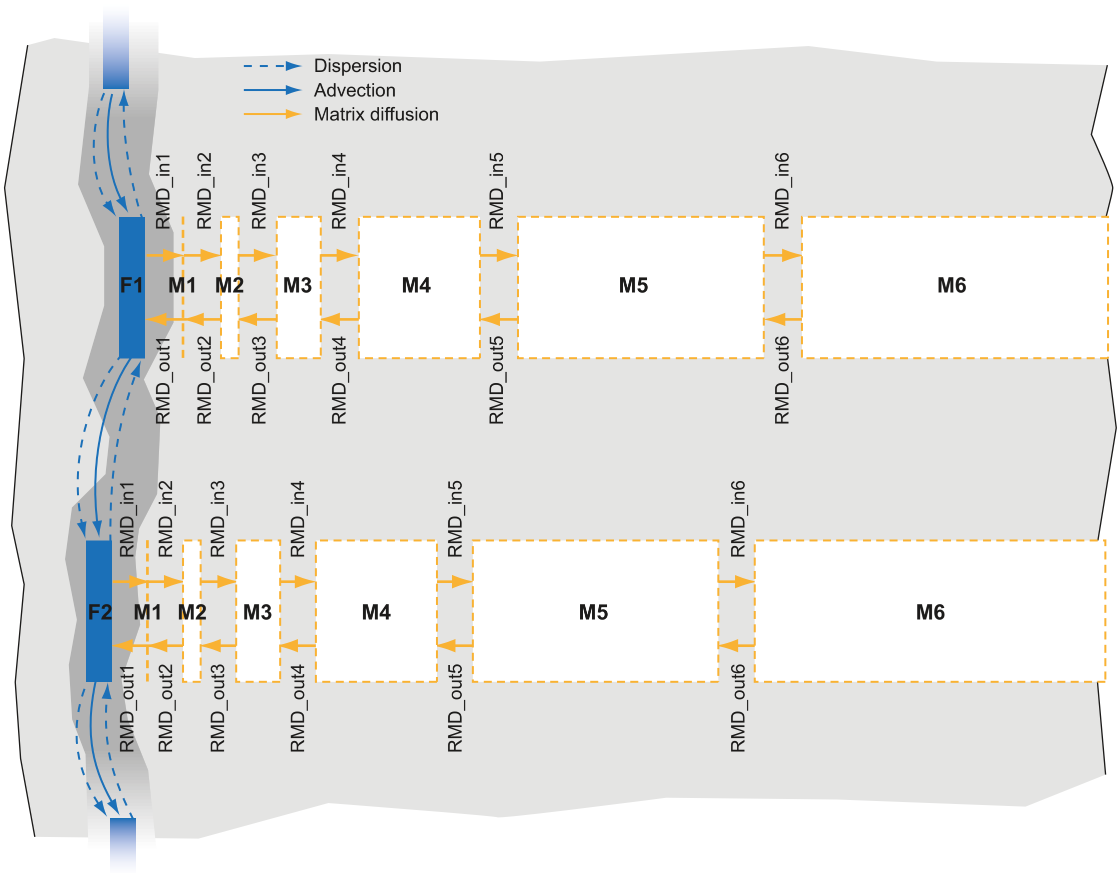


Figure 8-12. *Discretization of the geosphere in Amber. Equation 8-7 is used for advection, equations 8-11–8-12 for dispersion and equations 8-13–8-16 for matrix diffusion.*

R_m is the retardation in the rock matrix (–), given by

$$R_m = 1 + \frac{\rho\, K_d}{\theta} \tag{8-9}$$

ρ is the bulk density of the rock matrix (kg/m^3)

K_d is the sorption coefficient for the rock matrix (m^3/kg)

The following relationship was used to determine an approximate value of d_0

$$d_0 = \sqrt{\frac{2D_e t_f}{\theta\, R_m}} \tag{8-10}$$

where

D_e is the effective matrix diffusion coefficient (m^2/y)

t_f is the advective travel time (y)

d_0 was determined to be 0.0001 m based on plutonium data, since plutonium is the most strongly sorbed radionuclide and therefore requires the most sensitive resolution. This value of d_0 was used for all radionuclides.

The forward dispersive transfer rate (along the fracture), $\lambda_{ij,Disp}$ (y^{-1}), is given by

$$\lambda_{ij,Disp} = \frac{\dfrac{v \cdot L_{tot}}{R_f P_e} - \dfrac{v \cdot L_i}{2 \cdot R_f}}{L_i^2} \tag{8-11}$$

where

L_{tot} is the total flow path length (m)

P_e is the Peclet number (–)

The backward dispersive transfer rate, $\lambda_{ij,Disp}$ (y^{-1}), is given by

$$\lambda_{ji,Disp} = \frac{\dfrac{v \cdot L_{tot}}{R_f P_e} - \dfrac{v \cdot L_i}{2 \cdot R_f}}{L_j^2} \tag{8-12}$$

where

L_j is the length of compartment j (m)

The rate of diffusion from the fracture into the initial matrix compartment, λ_{RMD_in1}, is given by

$$\lambda_{RMD\_in1} = \frac{2a_w D_e}{R_f d_1} \tag{8-13}$$

where

d_1 is the depth of the initial matrix compartment (m)

The rate of matrix diffusion from compartment j to compartment $j+1$ is given by

$$\lambda_{RMD\_inj,j+1} = \frac{2D_e}{\theta R_m d_j \left(d_j + d_{j+1}\right)} \tag{8-14}$$

where

d_j is the depth of the matrix compartment j (m)

d_{j+1} is the depth of the matrix compartment $j+1$ (m)

The rate of diffusion from the initial matrix compartment into the fracture, λ_{RMD_out1}, is given by

$$\lambda_{RMD\_out1} = \frac{2D_e}{\theta R_m d_1^2} \tag{8-15}$$

The rate of matrix diffusion from compartment $j+1$ to compartment j is given by

$$\lambda_{RMD\_inj+1,j} = \frac{2D_e}{\theta R_m d_{j+1}\left(d_j + d_{j+1}\right)} \tag{8-16}$$

The data used for geosphere transport are shown in Table 8-2.

Table 8-2. Compilation of data for geosphere transport.

Parameter	Value	Reference
Peclet number, P_e (–)	10	SAFE project's Data Report /SKB 2001c/.
Flow-wetted surface area, a_w, (m^2/m^3)	120	SAFE project's Data Report /SKB 2001c/.
Matrix porosity, θ, (–)	0.005	SAFE project's Data Report /SKB 2001c/.
Density of rock matrix	2,600	/Thomson et al. 2008b/.
Depth of thin matrix layer, d0 (m)	0.0001	Fitted /Thomson et al. 2008b/ so that the total depth for matrix diffusion is 2 m, which was previously used in the SAFE project's calculations /Lindgren et al. 2001/.
Depth of 1st matrix compartment, d1 (m)	0.0005	
Depth of 2nd matrix compartment, d2 (m)	0.0025	
Depth of 3rd matrix compartment, d3 (m)	0.0125	
Depth of 4th matrix compartment, d4 (m)	0.0625	
Depth of 5th matrix compartment, d5 (m)	0.3125	
Depth of 6th matrix compartment, d6 (m)	1.6095	

8.3.8 Description of calculations in the biosphere

Analysis of radionuclide transport in the biosphere due to release in the geosphere and resulting exposure of humans and biota was done for each calculation case. The dose calculations were performed with models implemented in Pandora /Åstrand et al. 2005/, while probabilistic simulations of the Pandora models and uncertainty and sensitivity analyses were performed with the software package Eikos /Ekström and Broed 2006/. A detailed description of the models and the calculation methods for the biosphere analysis is provided in the background report for biosphere calculations /Bergström et al. 2008/. A brief summary is provided below.

In the preceeding safety assessment for SFR 1 it was found that C-14 is the radionuclide that gives the highest dose contribution /Lindgren et al. 2001/. Since C-14 is of such great importance for the result, the models used in the preceding safety assessment have been evaluated. This resulted in new biosphere models for C-14 for SAR-08 /Avila and Pröhl 2008/. In the following text, the model used to calculate the effects of releases of C-14 to the biosphere is first presented, plus an explanation of how the dose calculations are performed. This is followed by a description of the model used for the other radionuclides judged to be of interest for the assessment.

Model for C-14

The model used for C-14 is based on the specific activity approach, which is recommended by UNSCEAR and IAEA for dose calculations from releases of C-14 to the environment from nuclear installations. The most important assumption in these models is that the long-term behaviour of C-14 is modulated by the natural cycle for stable carbon (C-12) and that the isotopic equilibrium between C-14 and C-12 is achieved with a constant isotopic ratio (specific activity), i.e. the same specific activity (expressed in Bq/g C) will be observed in all parts of the biosphere. Furthermore, several realistic and conservative assumptions were made to obtain simple equations for calculating the specific activity of C-14. These assumptions are documented and explained in the background report to the C-14 model /Avila and Pröhl 2008/.

The specific activity model for C-14 was used to calculate dose to humans in ecosystems than can receive releases from the geosphere during different periods: mire, forest, agricultural land, coastal area and lake. The specific activity model for C-14 was also used to calculate the dose from exposure as a consequence of use of a well for drinking water and for irrigation of vegetables. The exposure from C-14 in ecosystems downstream is always judged to be lower than the exposure from the ecosystem that receives the release from the geosphere. This is a direct consequence of the fact that isotope dilution is irreversible, in other words once C-14 has been mixed with a given amount of C-12 the concentration cannot increase again /Sheppard et al. 2006/.

The following exposure pathways were included in the calculation of dose from C-14:
- ingestion of contaminated food and water in both terrestrial and aquatic ecosystems,
- inhalation of contaminated air in terrestrial ecosystems.

Exposure by external irradiation has been neglected, as C-14 is a pure low-energy beta emitter.

Model for all other radionuclides besides C-14

The biosphere calculations for all radionuclides except C-14 were carried out with landscape models, which consist of coupled biosphere objects. Within each biosphere object, radionuclide transport is modelled with ecosystem models (box models that describe an ecosystem). By including the flow of radionuclides between biosphere objects, landscape models can model radionuclide transport over a larger area than if only individual ecosystem models are used, as in the SAFE project.

Three landscape models were used in the biosphere calculations: One that represents today's situation and two that represent future conditions as a result of the ongoing shoreline displacement in the area. For each biosphere object (defined on the basis of its catchment area), a representative ecosystem model is selected, depending on the period. The ecosystem models that are used are the same as in SR-Can and are presented under separate headings below.

Figure 8-13 shows the landscape model that is used up to 5,000 years after repository closure. During that time, before shoreline displacement has caused the repository to be located beneath the land, each biosphere object (the numbered squares in the figure) represents a different sea basin. During the period from 5,000 years to 7,000 post-closure, a landscape model is used where objects 11 and 4 are lakes and the rest are sea basins. After 7,000 years a third landscape model is used where objects 11, 4 and 2 are mires and 3 and 1 are sea basins.

The fluxes of radionuclides between terrestrial and aquatic objects are assumed to be directly proportional to the fluxes of water through upstream objects. The water fluxes were estimated from the average run-off in the landscape, the areas of the objects and their associated catchment areas or from retention times. Radionuclides in both dissolved and particulate form are included in the calculations. Since the exposure takes place from a mire land, calculations were also performed where agricultural land or forest land has been formed in the mire land.

The exposure pathways that were considered in the landscape models were food ingestion for all types of biosphere objects, water ingestion for lakes, inhalation and external exposure for mire, forest and agricultural lands.

Ecosystem model for coast

The coastal model in Figure 8-14 consists of five different compartments that represent:
- The free water volume
- Suspended matter
- Pore water in the upper sediment layer
- Solid matter in the upper sediment layer
- Deeper sediment

The transfer of radionuclides takes place between compartments and to other objects due to advection, sedimentation, resuspension, sorption etc. The background report for the biosphere calculations /Bergström et al. 2008/ contains a description of the equations that were used to describe the processes and the input data that were used in the analysis.

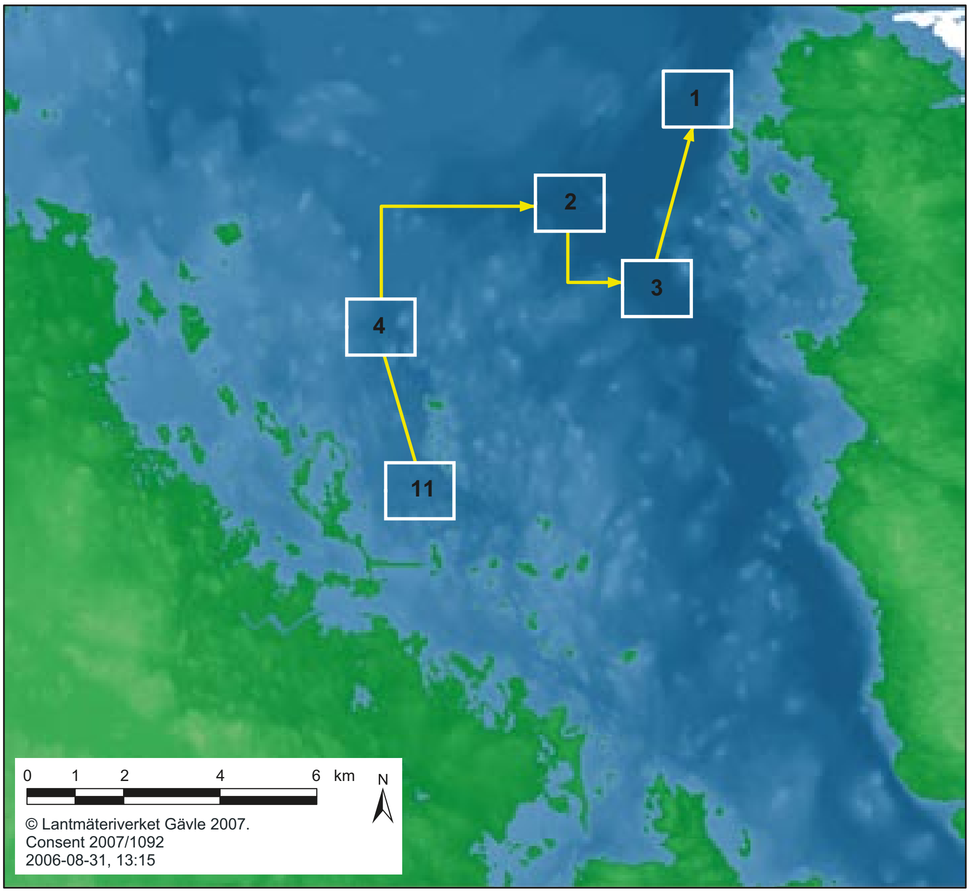


Figure 8-13. *Schematic description of the landscape model that is used up to 5,000 years post-closure when all biosphere objects are sea basins. Object 1 represents the Baltic Sea. The arrows show the direction of downstream water fluxes. The underlying map shows today's shoreline.*

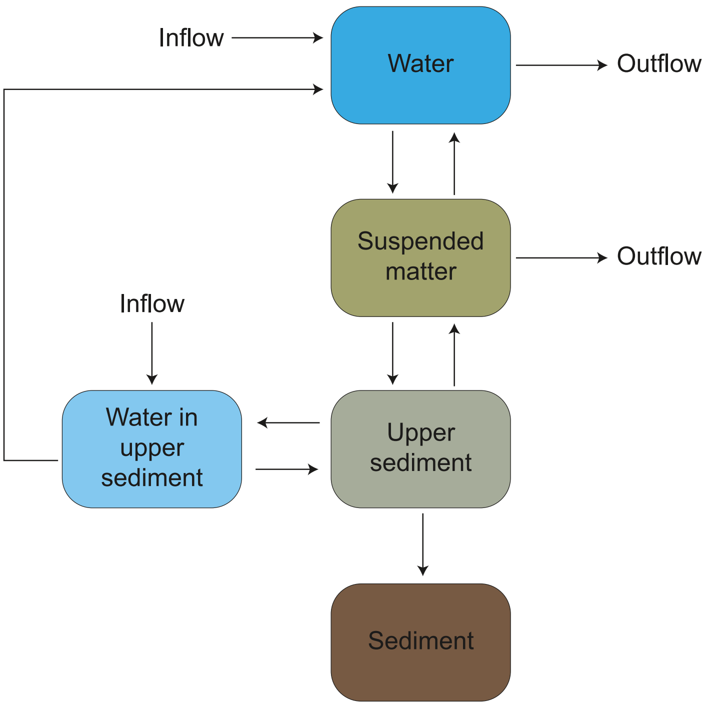


Figure 8-14. *Schematic description of the model for calculating the turnover of radionuclides in sea basins /Bergström et al. 2008/.*

Ecosystem model for lake

The compartments that are used to describe the lake object resemble those for the coast, Figure 8-14, but data and equations for certain processes are different than for the coast. Processes and data are described in the background report for the biosphere calculations /Bergström et al. 2008/.

Ecosystem model for mire

The mire, Figure 8-15, is described with the aid of two compartments:

- Solid matter in the form of organic and particulate material
- Pore water

The transfer of radionuclides takes place between the solid matter and the pore water. The radionuclides are transported further via runoff. The background report for the biosphere calculations /Bergström et al. 2008/ contains a description of the equations that were used to describe the processes and the input data that were used in the analysis.

Ecosystem model for well

A well could possibly be drilled so that it comes into contact with the water that passes through the repository parts, or directly into the repository. Dose calculation is therefore also done for exposure from wells. There the inflow varies slightly depending upon whether it is an intrusion well drilled by accident or a well in the discharge area. The calculation case "Wells" is described in section 8.4.11.

Doses from well in discharge area

Doses from a release to a well located in the repository's discharge area have been estimated by assuming that the entire release from the geosphere is completely mixed with the water in the well, which is used as drinking water and for irrigation of vegetables. The radionuclide concentration in the well water was calculated by dividing the radionuclide release by the well yield. The well yield was estimated from measurements from present-day near-coastal wells in Östhammar Municipality, see Chapter 4, section 4.7.3. The doses obtained from use of well water for irrigation were calculated with the model described in /Avila and Pröhl 2008/ for C-14 and with the model described in /Bergström et al. 2008/ for all other radionuclides.

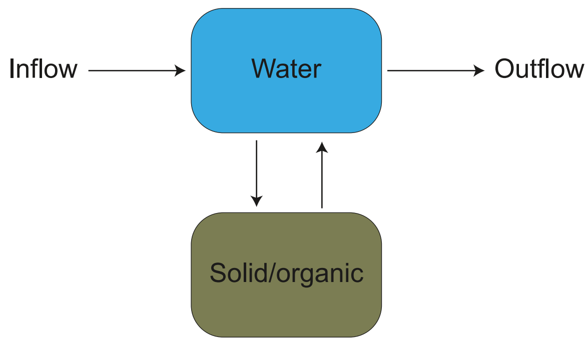


Figure 8-15. *Schematic description of the model for calculating the turnover of radionuclides in a mire /Bergström et al. 2008/.*

Doses from intrusion well

Doses from a well drilled directly into the repository have been calculated based on the radionuclide concentration in the water in the gravel backfill that surrounds each repository part. Annual dose is obtained by assuming that the annual water consumption is taken from this well.

Probabilistic calculations in the biosphere

The specific activity model for C-14 and the landscape models are used to make conservative estimates of the dose to the potentially most exposed individual in the different calculation cases. The dose calculations were made probabilistic in two steps /Bergström et al. 2008/:

1) Probability distributions for maximum annual effective dose for different time periods were generated by running the C-14 models and the three landscape models with a constant release rate of 1 Bq/y. The simulations for the landscape models were carried out for a time period of 20,000 years so that the equilibrium concentrations for the relevant radionuclides were achieved. However, the calculations showed that most radionuclides achieve equilibrium in a much shorter time /Bergström et al. 2008/.
2) Probability distributions for release to the biosphere for each time period from probabilistic near- and far-field calculations /Thomson et al. 2008a/ were multiplied by the probability distributions calculated for the biosphere for the corresponding time period.

Impact on biota

The biosphere analysis also included analyses of the impact of the releases on other biota than man. These analyses were carried out with a method developed in the EU project ERICA, see Chapter 10, section 10.1.2. This method is based on comparing conservative estimates of concentrations in different media such as water, sediments, air and soil with EMCLs (Environmental Media Concentration Limits). The EMCLs have been conservatively determined for a benchmark dose rate. This means that if the conservatively determined concentrations for different media are lower than these EMCLs, the ERICA project concludes that the risk for biota is negligible. In this analysis, radionuclide concentrations in soil, sediments and water have been calculated for the entire simulation period in the model for C-14 and the landscape models.

8.4 Calculation cases

Based on the scenario analysis carried out in Chapter 7, a number of calculation cases have been arrived at. The scenarios and calculation cases presented in Chapter 8 are summarized in Table 8-3. Where possible the calculation case has been given the same name as the scenario. In cases where a scenario contains several calculation cases, they have been given other names, see for example the scenario “Early freezing of the repository”, which contains two calculation cases where the BMA repository freezes at an early stage and two calculation cases where the repository is affected by extreme permafrost.

Table 8-3. Overview of scenarios and calculation cases.

Scenario category	Scenario	Calculation case	Comment	Section background report /Thomson et al. 2008b/
Main scenario	Main scenario's Weichselian variant	Weichselian variant	The climate evolution is expected to be a repeat of the latest glaciation. Permafrost is assumed to inhibit radionuclide transport. Closure plan, disposal inventory and system performance follow best estimates.	2.2.1
	Main scenario's greenhouse variant	Greenhouse variant	Human activity is expected to influence the climate and cause a longer initial period of temperate climate, compared with the Weichselian variant. The onset of permafrost, which is assumed to inhibit radionuclide transport, occurs later. Closure plan, disposal inventory and system performance follow best estimates.	2.2.5
Less probable scenarios	Earthquake	Earthquake		–
	Early freezing of the repository	Early freezing in main scenario's Weichselian variant (BMA repository)	The barriers in the BMA repository freeze during the permafrost at 25,000 AD 25,000.	2.2.4
		Early freezing in main scenario's Weichselian variant (BMA repository) with talik	The barriers in the BMA repository freeze during the permafrost at 25,000 AD. Radionuclide transport can occur during permafrost due to the presence of taliks.	
		Extreme permafrost	Extreme permafrost that inhibits radionuclide transport.	2.2.6
		Extreme permafrost with talik	Extreme permafrost where radionuclide transport can occur due to the presence of taliks.	2.2.7
	Talik	Talik	Like the main scenario's Weichselian variant but radionuclide transport can occur during periods of continuous permafrost due to the presence of taliks.	2.2.2
	High concentrations of complexing agents	High concentrations of complexing agents	Like the main scenario's Weichselian variant but high concentrations of complexing agents are assumed to reduce sorption coefficients for certain radionuclides.	2.2.8
	Gas-driven advection	Gas-driven advection	Like the main scenario's Weichselian variant but radionuclide transport is affected by increased gas generation in the silo.	2.2.9
	Wells	Well in discharge area	Drinking water well may be drilled in the repository's discharge area at any time except when the repository is located under water or when periglacial or glacial conditions prevail.	2.2.10
		Intrusion well in repository	Considers doses via inadvertent drilling of drinking water well directly down into the different repository parts.	2.2.10
Residual scenarios	Alternative inventory	Alternative inventory	Like the main scenario's Weichselian variant but the repository is assumed to contain the maximum permissible amount of radionuclides.	2.2.3
	Loss of barrier function, near-field I	No sorption in the near-field	Like the main scenario's Weichselian variant but sorption in the near-field is excluded.	2.2.11
	Loss of barrier function, near-field II	Early degradation of engineered barriers	Like the main scenario's Weichselian variant but the barriers in the silo and the BMA repository degrade at 5,000 AD.	2.2.13
	Loss of barrier function, far-field	Loss of barrier function, far-field	Like the main scenario's Weichselian variant but the geosphere is excluded.	2.2.12
	Abandoned unclosed repository	Abandoned unclosed repository	The repository is left unclosed.	–

8.4.1 The main scenario's Weichselian variant

The main scenario comprises two calculation cases: The Weichselian variant and the greenhouse variant. This section describes the Weichselian variant (Figure 8-16), but many premises are common to the two calculation cases. The next section describes what is specific for the greenhouse variant.

The climate evolution in the main scenario's Weichselian variant is based on a reconstruction of the conditions during the latest glacial cycle, including the Weichselian glaciation /Vidstrand et al. 2007/. The climate evolution in the calculation case has been simplified compared with the reference evolution, section 6.2.2. The simplification entails that brief periods with changed climate have been excluded so that the evolution only contains distinct periods with different climatic conditions and transitions between them, see Figure 8-17 and Figure 8-18. The brief periods that have been excluded occur early, and therefore the dose consequences are not affected, since the maximum release comes later.

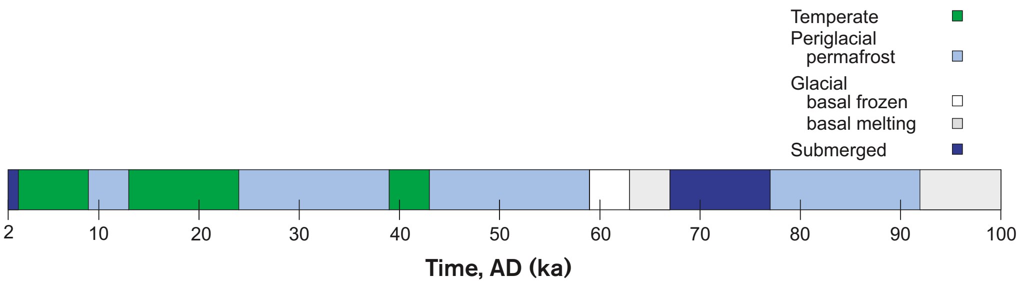


Figure 8-16. *Climate evolution according to the main scenario's Weichselian variant based on a reconstruction of the conditions during the latest glacial cycle.*

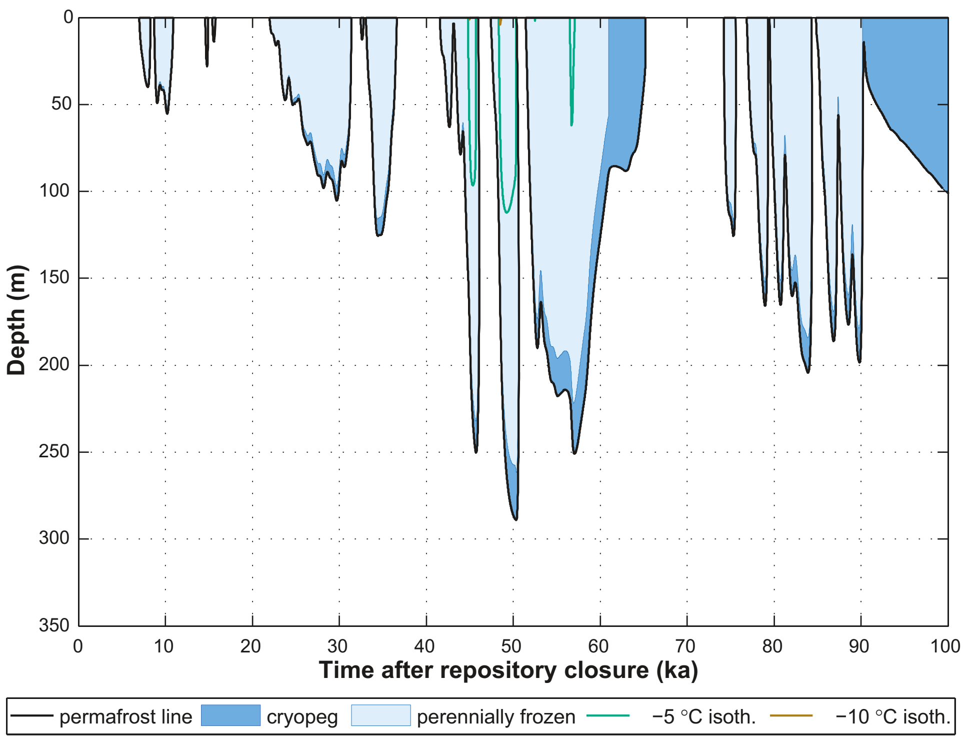


Figure 8-17. *Calculated permafrost depth and depth of the –5° C and –10° C isotherms at Forsmark for the main scenario's Weichselian variant, based on 1D simulations of permafrost. For detailed information on these simulations, see /SKB 2006d, Vidstrand et al. 2007b/.*

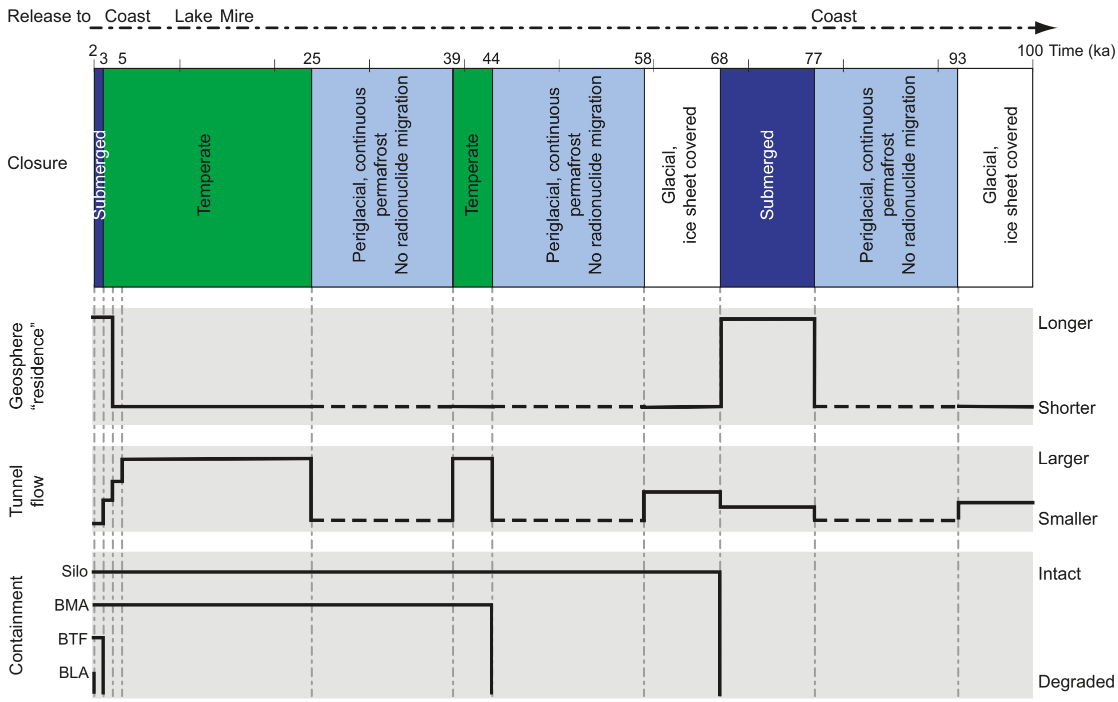


Figure 8-18. *Summary of the main scenario's Weichselian variant. Modified from /Thomson et al. 2008a/.*

The Weichselian-based variant starts with a period of temperate climatic conditions that lasts for 8,000 years. Then comes the first periglacial period where permafrost conditions dominate. This period is followed by a return to temperate conditions, which are gradually supplanted by permafrost conditions. Extended periglacial periods with deep permafrost exist between 44,000 and 58,000 years and between 77,000 and 93,000 years AD. The permafrost reaches down to the repository during these periods, see Figure 8-17. The temperature in the bedrock during the first permafrost period with deep permafrost falls to about –10°C and during the second period to about –5°C, see Figure 6-22. The maximum depth of the permafrost is around 250 m and is reached after 50,000 years, see Figure 8-17.

In the main scenario's Weichselian variant, the ice sheet advances in over the Forsmark region after around 60,000 years. The second, longer glacial period ensues after about 90,000 years. Permafrost growth stops when the ice sheet covers the site and begins to grow thinner. This trend, with gradual development of more dominant and longer permafrost periods and glaciation, is a result of the increasingly cold climate during the glacial cycle.

As the ice sheet advances, the upper part of the rock is insulated from the cold climate, and eventually basal melting takes place beneath the ice. In the Weichselian variant of the main scenario, the Forsmark region is covered with ice for a total of about 30,000 years. Basal melting dominates during this time. The maximum thickness of the ice in the Forsmark region is about 3 km. Permafrost prevails in this variant for more than 40,000 years of the analyzed period.

The main scenario's Weichselian variant is summarized in Figure 8-18. The early permafrost period around 10,000 AD is sporadic, which means that groundwater movements cannot be excluded. This period has therefore been regarded as temperate in the calculations, which can be seen in Figure 8-18.

Table 8-4 summarizes the different climate domains in chronological order plus flow factors used in the calculations. The flow factors are the result of generic model studies /Vidstrand et al. 2007/ of how the flow is affected by different future climatic conditions compared with today's climate.

Table 8-4. Summary of the climate domains and flow factors for the main scenario's Weichselian variant /Holmén and Stigsson 2001a, 2001b, Vidstrand et al. 2007/.

Climate domain	Year (thousands of years)	Comment
Temperate	2–25	Flow factor 1.
Periglacial, continuous permafrost	25–39	Flow factor 0 for the Weichselian variant when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere. Flow factor 10 for calculation case "Talik".
Temperate	39–44	Flow factor 1.
Periglacial, continuous permafrost	44–58	Flow factor 0 for the Weichselian variant when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere. Flow factor 10 for calculation case "Talik".
Glacial, ice sheet	58–68	Flow factor 0.5.
Submerged	68–77	Flow factor 0.01 for tunnels. Flow factor 1 for the silo and the geosphere.
Periglacial, continuous permafrost	77–93	Flow factor 0 for the Weichselian variant when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere. Flow factor 10 for calculation case "Talik".
Glacial, ice sheet	93–100	Flow factor 0.2.

Near-field

The waste in SFR consists of operational waste from 50 years of nuclear energy production, see Table 8-1, and similar types of waste from other industry, research and medical care. The following initial state is assumed during operation and at closure of the repository (see also Chapter 4):

- The waste in the silo consists chiefly of ion exchange resins in cement or bitumen matrices. These are placed in shafts and the voids are grouted with permeable cement. The silo is closed with a metre-thick concrete lid and covered with 1.5 metres of sand/bentonite mixture (90/10). Other voids are filled with sand or gravel.
- The waste in the BMA repository consists of ion exchange resins, scrap metal and waste in concrete or bitumen matrices, packed in a similar way as in the silo. The BMA repository is divided into 15 compartments separated by concrete walls. As soon as a compartment is full it is closed with a concrete lid and concrete is poured over the lid. Other voids outside the disposal compartments are filled with sand or gravel.
- The 1BTF and 2BTF repositories contain dewatered low-level ion exchange resins in concrete tanks and drums with ashes (1BTF). The tanks are grouted with concrete and the spaces between tanks and walls are filled with cement-stabilized sand.
- The waste in the BLA repository consists mostly of low-level trash and scrap metal in steel containers. No backfill grouting.
- The entrances to the deposition tunnels and to the silo are closed with concrete plugs and bentonite.

In the main scenario it is assumed that the quality of the engineered barrier system complies with the design specification. This means that the concrete structures do not contain large cracks – small penetrating cracks caused by stresses in the material may occur, however – and that bentonite and sand/bentonite barriers are assumed to be homogeneous. It is further assumed that concrete tanks and concrete moulds are intact at closure and do not contain large penetrating cracks. Steel containers are not intended to serve as barriers and are assumed to be neither watertight nor gastight.

At closure the drainage system will be taken out of operation, and within a few years (about ten years for the silo which is saturated last), the repository will be filled with groundwater /Holmén and Stigsson 2001a/. Since this time is short, the repository is assumed to be water-filled immediately after closure in the continued analysis. Shoreline displacement affects the flow through all repository parts except the silo which is not noticeably affected. During the first 3,000 years the flow increased by up to a factor of 6, see Table 8-5. After that, shoreline displacement does not affect the groundwater flow to any great extent, see Table 6-9. In the radionuclide transport calculations, the flow has been changed in steps according to Table 8-5. The radionuclide inventory in the different compartments described in 8.3.7 has been kept constant between each step. How the long-term hydrogeological conditions in the vicinity of the repository may vary has been estimated for the different climate domains, see section 6.6.2.

When the groundwater has penetrated into the different parts of the repository it comes into contact with the waste and radionuclides in the waste can dissolve in the water. No limits have been set on the solubility of the radionuclides in cement or bitumen, which means that dissolved radionuclides can be transported from the waste matrix, through the packaging and the surrounding concrete, bentonite and sand out into the repository. Radionuclide transport takes place by diffusion and advection with the groundwater flow. The quantity of radionuclides released from each repository part depends on the radionuclide concentration in the water, the diffusion and sorption properties of the barrier materials, the size and distribution of the water flow in the barriers, and how these factors change over time.

Initially the groundwater is assumed to be saline (see Table 6-5), but land uplift and shoreline displacement cause a shift to fresh water (see Table 6-12) after about 1,000 years. Cement and concrete in the repository will result in a high pH in the inflowing water during the first period, and the ionic strength of the water will be high since the water is initially saline and additional salts are dissolved from the concrete /Höglund 2001, Cronstrand 2007/.

Transport of radionuclides in the near-field is retarded by sorption in the engineered barriers. The sorption coefficients for concrete and cement and for gravel and sand are summarized in Table 8-6 (not applicable for the calculation case "Complexing agents"). The values are representative of fresh concrete and cement. Degradation of concrete and cement leads to leakage of constituents that reduces the capacity of the barriers to maintain an alkaline pH. Since an alkaline pH favours sorption, it is assumed that the sorption capacity of these barriers is reduced to the same level as for sand and gravel.

The sorption coefficients for gravel and sand have been used in the calculations for the time period when the barriers are expected to be degraded: At 3000 AD for the BTF repositories, at 44,000 AD for the BMA (from the start of the second permafrost period) and at 68,000 AD for the silo after degratiation), in the main scenario's Weichselian variant.

Table 8-5. Total groundwater flow through the different repository parts calculated in the SAFE project /Holmén and Stigsson 2001a, 2001b, SKB 2001c/.

Repository part	Total groundwater flow [m^3/y]			
	Immediately after closure and water saturation	3,000 AD	4,000 AD	5,000 AD
Silo: backfill (top)	0.53	1.4	2.2	2.2
Silo: encapsulation	0.23	0.22	0.16	0.23
BMA: encapsulation	0.07	0.13	0.26	0.28
BMA: total	8.7	36.7	52.7	54.7
1BTF: waste	2.4	2.7	6.8	7.8
1BTF: total	7.5	19.4	26.4	30.7
2BTF: waste	2.4	3.0	6.0	6.8
2BTF: total	6.7	17.6	27.7	29.6
BLA: waste	9.6	19.4	35.0	38.4
BLA: total	13.6	33.1	50.2	54.2

Table 8-6. Sorption coefficients [m³/kg] for concrete and cement and for sand and gravel /Cronstrand 2005/.

	Concrete and cement			Sand and gravel		
	Minimum	Recom-mended	Maximum	Minimum	Recommended	Maximum
H	0	0	0	0	0	0
C org.	0	0	0	0	0	0
C inorg.	0.01	0.2	4	0.00002	0.0005	0.01
Cl	0.0006	0.006	0.06	0	0	0
Co	0.004	0.04	0.4	0.001	0.01	0.1
Ni	0.008	0.04	0.2	0.002	0.01	0.05
Se	0.0001	0.006	0.4	0.00001	0.0005	0.03
Sr	0.0005	0.001	0.05	0.00002	0.0001	0.0005
Mo	0.0001	0.006	0.4	0	0	0
Nb	0.1	0.5	2.5	0.1	0.5	2.5
Tc(IV)	0.05	0.5	5	0.03	0.3	3
Ag	0.00002	0.001	0.05	0.0002	0.01	0.5
Sn	0.025	0.5	10	0	0	0.01
I	0.0003	0.003	0.03	0	0	0
Cs	0.0001	0.001	0.01	0.001	0.01	0.12
Ho	1	5	25	0.2	1	5
Np(IV)	1	5	25	0.2	1	5
Pu(IV)	1	5	25	0.2	1	5
Am	0.2	1	5	0.2	1	5

The sorption coefficients for bentonite in Table 8-7 are determined for the MX-80 bentonite that was used in SR-Can /Ochs and Talerico 2004/ but are also deemed to be valid for the GEKO/Ql bentonite used in SFR 1. The values in Table 8-6 and Table 8-7 show minimum, recommended and maximum values in the log-triangular distribution used in the probabilistic radionuclide transport calculations. The recommended value has been used in the deterministic calculations. The values for the sand/bentonite mixture (90% sand and 10% bentonite) are calculated as weighted mean values based on the sand/bentonite distribution.

Even though it is known that iron oxide binds many elements, the corrosion products of iron and steel have not been taken into account in the radionuclide transport calculations /Thomson et al. 2008a/. The waste in SFR 1 contains chemicals that can form complexes with radionuclides and thereby affect sorption. Cellulose, which is present both in the waste and as an additive in cement, can form isosaccharinic acid (ISA), which is a strong complexing agent. The presence of moderate concentrations of ISA has been taken into account in the choice of sorption coefficients for concrete.

Values of effective diffusivity, particle density and porosity have mainly been determined for the SAFE project /SKB 2001c/. The effective diffusivity for a fresh concrete structure is $3 \cdot 10^{-12}$ m²/s and for an aged structure $3 \cdot 10^{-11}$ m²/s, based on a porosity of 15%, a geometric factor of 0.01 for fresh and 0.1 for aged concrete structure and a diffusivity of $2 \cdot 10^{-9}$ m²/s for free groundwater[1]. The higher value of the geometric factor for aged concrete was selected because the inner pore structure can be less complex due to recrystallization of calcium silicate hydrate gel.

[1] Effective diffusivity, D_e, is defisned as follows /SKB 2001c/.

$D_e = D_w \varepsilon \frac{\delta}{\tau^2}$, where D_w is diffusivity in water (m²/s), ε is porosity, δ is the constrictivity factor and τ is the tortuosity factor. The geometric factor, GF, is defined as $GF = \frac{\delta}{\tau^2}$.

Table 8-7. Sorption coefficients [m^3/kg] for bentonite and sand/bentonite /Ochs and Talerico 2004/.

	Bentonite			Sand/bentonite		
	Minimum	Recommended	Maximum	Minimum	Recommended	Maximum
H	0	0	0	0	0	0
C org.	0	0	0	0	0	0
C inorg.	0	0	0	0.000018	0.00045	0.009
Cl	0	0	0	0	0	0
Co	0.03	0.3	3.3	0.0039	0.039	0.42
Ni	0.03	0.3	3.3	0.0048	0.039	0.375
Se	0.003	0.04	0.4	0.000309	0.00445	0.067
Sr	0.0009	0.005	0.031	0.000108	0.00059	0.00355
Mo	0	0	0	0	0	0
Nb	0.2	3	45	0.11	0.75	6.75
Tc	2.3	63	1,764	0.257	6.57	179
Ag	0	0	15	0.00018	0.009	1.95
Sn	2.3	63	1,764	0.23	6.3	176
I	0	0	0	0	0	0
Cs	0.018	0.11	0.6	0.0027	0.02	0.168
Ho	0.8	8	93	0.26	1.7	13.8
Np	4	63	1,113	0.58	7.2	116
Pu	4	63	1,111	0.58	7.2	116
Am	10	61	378	1.18	7	42.3

An effective diffusivity of $3 \cdot 10^{-10}$ m^2/s was assumed for the BTF repositories and the silo's concrete structures. The porosity of gravel was assumed to be 30%, and with a geometric factor of 1 the effective diffusivity of gravel is $6 \cdot 10^{-10}$ m^2/s /Freeze and Cherry 1979, SKB 2001c/. The effective diffusivity of bentonite was selected from estimates in SR-Can (MX-80) to be $4.6 \cdot 10^{-10}$ m^2/s /Ochs and Talerico 2004/. The effective diffusivity of sand/bentonite was selected to be $5 \cdot 10^{-10}$ m^2/s, based on a porosity of 25% and a geometric factor of 1.

The engineered barrier system in SFR 1 is designed to both limit radionuclide migration with the groundwater and provide a controlled pathway for gas release.

The barrier functions in the silo and BMA repositories will in all probability be functional for more than 10,000 years, while the barriers in the BTF repositories are thinner and are assumed to function for 1,000 years /Thomson et al. 2008a/. In the silo it is assumed that the bentonite erodes in conjunction with the retreat of the ice sheet after deglaciation in 68,000 AD. The concrete barriers in the silo and BMA repositories are expected to burst due to freezing when the permafrost reaches repository depth at the start of the second period of continuous permafrost in 44,000 AD /Emborg et al. 2007/. The plugs are assumed to degrade at the same time as the bentonite in the silo. Degradation in the silo changes the flow pattern towards more horizontal flows /Holmén and Stigsson 2001a/. Degraded barriers in the BMA repository increase the flow by a factor of 30, while the flow in the BTF repositories increased by a factor of about 2. The flow factors used in the calculations are summarized in Table 8-8. The flow factors have been estimated by comparing the results of hydrogeological calculations for the first 10,000 years with intact and degraded barriers, respectively /Holmén and Stigsson 2001a/. Based on hydrogeological calculations of degradation of plugs at an early stage /Holmén and Stigsson 2001a/, it is assumed that the tunnel flows increase, due to degraded plugs, by a factor of 1.3 for the silo and a factor of 2 for other repository parts.

Table 8-8. Flow factors for degraded barriers /Thomson et al. 2008a/.

	Flow factor	Comment
Silo	–	Different flow factors for different parts,for details see/Thomson et al. 2008a/.
BMA	30	Based on a potential increase in the groundwater flow rate through the encapsulation area that would have resulted in flows through the waste comparable to those in the BTF repositories.
1BTF	2	Assumes breached encapsulation, floor and side filling. Long term average value.
2BTF	2	Assumed to be the same as 1BTF.
BLA	–	No barriers are taken into account in BLA.

Most of the gases in the repository – such as hydrogen, carbon dioxide and methane – derive from anaerobic metal corrosion (primarily of steel but also of Al and Zn) and degradation of organic material, see Tables 6-7 and 6-8. The gas formed is expected to be able to escape from all repository parts (see section 6.4.4), but since gas evolution is mainly assumed to take place during the initial time period with release to the Baltic Sea (with low dose conversion factors), outward transport of radionuclides from the repository via gas is disregarded.

Geosphere

Radionuclides are transported with the groundwater flow in open fractures through the bedrock. The rock's ability to limit the outward transport of the radionuclides is primarily dependent on the magnitude of the groundwater flow, the transport resistance, the length of the flow paths and the exchange of radionuclides between the water and the rock. Retardation limits the radionuclide release to the biosphere by allowing a larger fraction of the radionuclides to decay. Soon after closure the repository is filled with water and the transport pathways from the repository to the surface become relatively short, since the flow is expected to be vertical. Release therefore takes place to the seabed above the repository. The hydraulic gradient is expected to be low, however, so the movement will be slow. Land uplift and shoreline displacement increase the hydraulic gradient, resulting in a more horizontal flow direction, with longer flow paths but a shorter breakthrough time. The area where the releases are expected to take place is located northwest of the repository, and the topography is such that a lake will probably form in this area. During periods of continuous permafrost, the geosphere is expected to freeze, causing the water flow, and thereby also the radionuclide flows, to stop. During periods of glaciation, the flows are expected to be very low and the groundwater is assumed to discharge at the edge of the ice sheet. The edge of the ice sheet may be situated at a very great distance from the repository, but also right next to it, which means that the flow through the repository could be great.

Estimates of flow directions and breakthrough times in the geosphere have been taken from hydrogeological calculations /Holmén 2007/ where different sets of values have been calculated for the time immediately after closure and 5,000 AD, Table 8-9. For flow paths lengths and breakthrough times, probability distributions have been determined for the two points in time (see Figures 6-16, 6-24, 6-17 and 6-26). These have been used for probabilistic calculations in the transport model.

Since there is a strong correlation between the groundwater flows in the near-field and transport parameters in the geosphere, it is important that near-field and geosphere parameters correspond in the transport calculations. To ensure correct usage of flow-related parameters in the models, predefined data are entered from files that handle data for the near-field's uncertainty factors as well as flow path lengths and breakthrough times for the geosphere data that are used. For the times in the transport calculations /Thomson et al. 2008a/ when flow path lengths and breakthrough times are lacking in the updated hydrogeological calculations /Holmén 2007/ – 3,000 AD and 4,000 AD – data for 2,000 AD and 5,000 AD are used.

Table 8-9. Median values of flow path lengths and breakthrough times in the geosphere /Holmén 2007/.

	Flow path length [m]		Breakthrough time [years]	
	Closure	5,000 AD	Closure	5,000 AD
BMA	67	425	86	22
BLA	72	503	40	26
1BTF	78	315	317	45
2BTF	78	412	272	36
Silo	66	388	495	72

Initially the groundwater is assumed to be saline, but land uplift and shoreline displacement cause a change to fresh water after about 1,000 years. When the ice sheet retreats in 68,000 AD and the repository is located beneath the surface of the sea, the groundwater is expected to become saline once again.

Sorption data in the geosphere are the same as those used in SR-Can /SKB 2006c/. The sorption factors were determined for crushed rock. In order to use them for solid rock, they have been corrected by factor of 0.1 in Table 8-10 /SKB 2006c/.

In order to calculate the effective diffusivity in the geosphere matrix, the diffusivity in free solution has been multiplied by formation factors (for Forsmark) /SKB 2006c/. These formation factors are based on in-situ measurements performed at a depth of between 100 and 1,000 m and are assumed to be affected by the rock stresses that exist at depth. The formation factor for shallow systems is probability greater, which means it is conservative to use values in /SKB 2006c/ for SFR. In a comparison between formation factors obtained in situ and in the laboratory, it was found that the latter were an order of magnitude greater /Liu et al. 2006/.

Table 8-10. Sorption data used for granitic rock [m^3/kg] from SR-Can /SKB 2006c/.

Element	Non-saline groundwater			Saline groundwater *		
	Minimum	Recommended	Maximum	Minimum	Recommended	Maximum
H	–	0	–	–	0	–
C (HCO_3^-)	$5\cdot10^{-5}$	$1\cdot10^{-4}$	$2\cdot10^{-4}$	$5\cdot10^{-5}$	$1\cdot10^{-4}$	$2\cdot10^{-4}$
C org.	–	0	–	–	0	–
Cl	–	0	–	–	0	–
Co*	Not taken into account due to half-life			$1\cdot10^{-3}$	$2\cdot10^{-3}$	$1\cdot10^{-2}$
Ni	$2.8\cdot10^{-3}$	$1.2\cdot10^{-2}$	$5.4\cdot10^{-2}$	$8.0\cdot10^{-4}$	$1.0\cdot10^{-3}$	$8.7\cdot10^{-3}$
Se	$5\cdot10^{-5}$	$1\cdot10^{-4}$	$5\cdot10^{-4}$	$5\cdot10^{-5}$	$1\cdot10^{-4}$	$5\cdot10^{-4}$
Sr*	Not taken into account due to half-life			$1.4\cdot10^{-6}$	$3.1\cdot10^{-5}$	$2.6\cdot10^{-3}$
Mo	–	0	–	–	0	–
Nb	$5\cdot10^{-2}$	$1\cdot10^{-1}$	$3\cdot10^{-1}$	$5\cdot10^{-2}$	$1\cdot10^{-1}$	$3\cdot10^{-1}$
Tc(IV)	$5\cdot10^{-2}$	$1\cdot10^{-1}$	$3\cdot10^{-1}$	$5\cdot10^{-2}$	$1\cdot10^{-1}$	$3\cdot10^{-1}$
Ag	$1\cdot10^{-2}$	$5\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-3}$	$5\cdot10^{-3}$	$1\cdot10^{-2}$
Sn	$1.2\cdot10^{-8}$	$1\cdot10^{-4}$	$1\cdot10^{-3}$	0	$1\cdot10^{-4}$	$1\cdot10^{-3}$
I	–	0	–	–	0	–
Cs	$1.7\cdot10^{-4}$	$1.8\cdot10^{-2}$	$9.6\cdot10^{-1}$	$4.0\cdot10^{-5}$	$4.2\cdot10^{-3}$	$2.0\cdot10^{-1}$
Ho	$1\cdot10^{-1}$	$2\cdot10^{-1}$	$5\cdot10^{-1}$	$1\cdot10^{-1}$	$2\cdot10^{-1}$	$5\cdot10^{-1}$
Np(IV)	$4.7\cdot10^{-3}$	$9.6\cdot10^{-2}$	2	$4.7\cdot10^{-3}$	$9.6\cdot10^{-2}$	2
Pu(IV)	$1\cdot10^{-1}$	$5\cdot10^{-1}$	1	$1\cdot10^{-1}$	$5\cdot10^{-1}$	1
Am)	$2.2\cdot10^{-2}$	1.3	$1.9\cdot10^{1}$	$2.2\cdot10^{-2}$	1.3	$1.9\cdot10^{1}$

* The period with saline groundwater includes the first 1,000 years in all calculation cases. Definitions of groundwater types are given in the Data Report for SR-Can /SKB 2006c/.

The possibility that anion exclusion could increase with depth was identified in /SKB 2006c/, and the effective diffusivity of anions was therefore divided by a factor of 10. In SAR-08 it has been considered to be on the borderline to over-conservative to perform this division for such a superficial matrix rock. Since anion exclusion is more important in non-saline than in saline water /Liu et al. 2006/, the compromise was struck of adopting the division of the effective diffusivity of anions by a factor of 10 for non-saline waters, but not for saline waters. The results are summarized in Table 8-11.

Surface ecosystems

A possible evolution of the surface ecosystems is described in Chapter 6, section 6.3. Following is a brief summary of how this evolution is reflected in the calculations. A more detailed description of dose calculations is found in /Bergström et al. 2008/.

At the time of closure, the discharge area is situated above the repository and consists of a basin in Öregrundsgrepen known as the SAFE Basin. Öregrundsgrepen has relatively large water volumes and short water residence times. In the biosphere model, Öregrundsgrepen is described as consisting of four interconnected basins, one of which is the SAFE Basin /Bergström et al. 2008/. This basin is the area immediately above SFR 1 and was selected on the basis of the area's bottom topography as an expected future sub-catchment. The SAFE Basin, together with surrounding basins, has been used to calculate doses from the calculated releases during the period up to around 5,000 AD. No great changes are expected in the area during the first 1,000 years, aside from a decrease in volume and average depth. Shoreline displacement gradually transforms the area during the next 9,000 years to a land area via archipelago, lakes and mires. The groundwater discharge area follows the change in the shoreline /Holmén and Stigsson 2001a/. Thus, radionuclides are expected to be discharged into the largest of the lakes formed in the model area from around 5,000 AD. In comparison with the coastal area, the lake has much lower water turnover and thereby longer radionuclide residence times. The lake is assumed to be so silted-up by 7,000 AD that it has now become a wetland, a mire. The outflow of radionuclides subsequently occurs to this mire until the next glaciation depresses the area below sea level. The releases are then assumed to take place to a coastal area. This coastal area is assumed to be comparable to today's with regard to both hydrological conditions and exposure pathways. Table 8-12 shows what type of ecosystem releases are assumed to occur to during different time periods for the main scenario's Weichselian variant. During periods with continuous permafrost there are no releases of radionuclides.

Table 8-11. Effective diffusivities (m^2/s) in granitic rock from the Data Report for SR-Can /SKB 2006c/.

	Non-saline groundwater			Saline groundwater		
	Minimum	Best estimate	Maximum	Minimum	Best estimate	Maximum
HTO	*	*	*	$3.1\cdot10^{-14}$	$9.1\cdot10^{-14}$	$2.9\cdot10^{-13}$
$C(CO_3)$	$1.6\cdot10^{-15}$	$4.6\cdot10^{-15}$	$1.4\cdot10^{-14}$	$1.6\cdot10^{-14}$	$4.6\cdot10^{-14}$	$1.4\cdot10^{-13}$
Cl	$2.6\cdot10^{-15}$	$7.6\cdot10^{-15}$	$2.4\cdot10^{-14}$	$2.6\cdot10^{-14}$	$7.6\cdot10^{-14}$	$2.4\cdot10^{-13}$
Co	*	*	*	$9.1\cdot10^{-15}$	$2.7\cdot10^{-14}$	$8.4\cdot10^{-14}$
Ni	*	*	*	$8.8\cdot10^{-15}$	$2.6\cdot10^{-14}$	$8.2\cdot10^{-14}$
Sr	*	*	*	$1.0\cdot10^{-14}$	$3.0\cdot10^{-14}$	$9.5\cdot10^{-14}$
Ag	*	*	*	$2.2\cdot10^{-14}$	$6.5\cdot10^{-14}$	$2.0\cdot10^{-13}$
I	$1.1\cdot10^{-15}$	$3.2\cdot10^{-15}$	$1.0\cdot10^{-14}$	$1.1\cdot10^{-14}$	$3.2\cdot10^{-14}$	$1.0\cdot10^{-13}$
Cs	*	*	*	$2.7\cdot10^{-14}$	$8.0\cdot10^{-14}$	$2.5\cdot10^{-13}$
Others	*	*	*	$1.3\cdot10^{-14}$	$3.8\cdot10^{-14}$	$1.2\cdot10^{-13}$

* Cation, data for saline groundwater are used according to above discussion (definitions of groundwater types are given in the Data Report for SR-Can /SKB 2006c/).

Table 8-12. Summary of different periods and relevant ecosystem for the main scenario's Weichselian variant.

Time (thousands of years)	Release is assumed to occur to
2–5	Coast
5–7	Lake
7–25	Mire
25–39	No release to biosphere, permafrost.
39–44	Mire
44–58	No release to biosphere, permafrost.
58–77	Coast
77–93	No release to biosphere, permafrost.
93–100	Coast

A forest ecosystem has been used during the periods when release takes place to land, see also /Bergström et al. 2008/.

It is pessimistically assumed in the dose calculations that the entire radionuclide outflow takes place to only one object, i.e. to a limited area. The principle for the calculations has been to concentrate the dose calculations on the most exposed individuals who obtain their annual energy demand from the most exposed area. In the dose calculations it is assumed that all ecosystems – coast, lake and mire – produce the annual energy demand expressed as 110 kg of organic carbon per person. In the aquatic ecosystems, this production is assumed to consist of fish, while for the mire it consists of game, mushrooms and berries.

The annual doses are calculated based on internal exposure from ingestion of food and water and the external dose during a year, in accordance with the IAEA /IAEA 2001/. The annual dose is constant for an individual, which is judged to be an acceptable simplification, since the releases occur over relatively long periods of time and are considered to be constant over a person's lifetime.

Wells may eventually be drilled in the repository or its discharge area, see section 6.5. These wells are, however, not included in the main scenario but are evaluated as a separate scenario, see Chapter 7, section 7.6.7. But they are included in the risk evaluation presented in Chapter 10.

8.4.2 Main scenario's greenhouse variant

The main scenario's greenhouse variant describes a climate evolution that includes human-induced climate change. The main scenario's greenhouse variant is based on the greenhouse variant described in the section on climate change in the reference evolution, Chapter 6, section 6.2.2. However, the evolution has been simplified (as for the main scenario's Weichselian variant) to provide a clearer picture with more continuous periods with the different climate domains, see Figure 8-19.

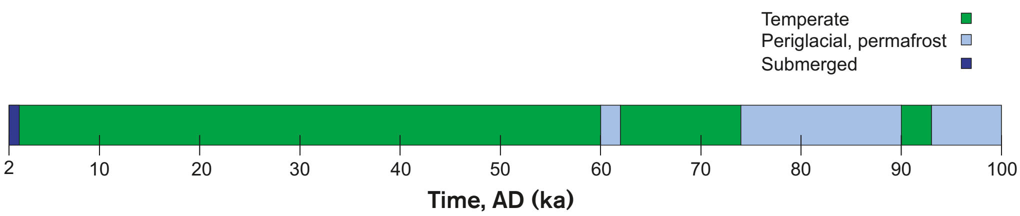


Figure 8-19. *Climate evolution according to the main scenario's greenhouse variant.*

In the main scenario's greenhouse variant it is assumed that the first 50,000 years will be temperate, followed by the first mild period of the climate evolution in the Weichselian variant. The start of the subsequent glaciation is accordingly assumed to be shifted forward in time, and the glaciation periods during the coming 100,000 years will be shorter than in the main scenario's Weichselian variant. This results in 70,000 years of temperate climatic conditions, aside from a short initial permafrost period at 60,000 years. Periods with heavy permafrost start around 75,000 AD. Permafrost prevails in this variant for just under 30,000 years. In this variant, the permafrost reaches down to a maximum depth of 250 metres.

The main scenario's greenhouse variant is summarized in Figure 8-20. The early permafrost period around 60,000 AD is sporadic, which means that groundwater movements cannot be excluded. This period has therefore been regarded as temperate in the calculations, which can be seen in Figure 8-20.

Table 8-13 summarizes the different climate domains in chronological order plus the flow factors used in the calculations.

Table 8-13. Summary of the climate domains and flow factors from long-term hydrogeological modelling studies for the main scenario's greenhouse variant /Holmén and Stigsson 2001a, 2001b, Vidstrand et al. 2007/.

Climate domain	Year (thousands of years)	Comment
Temperate	0–75	Flow factor 1.
Periglacial, continuous permafrost	75–100	Flow factor 0 for the greenhouse variant when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere.

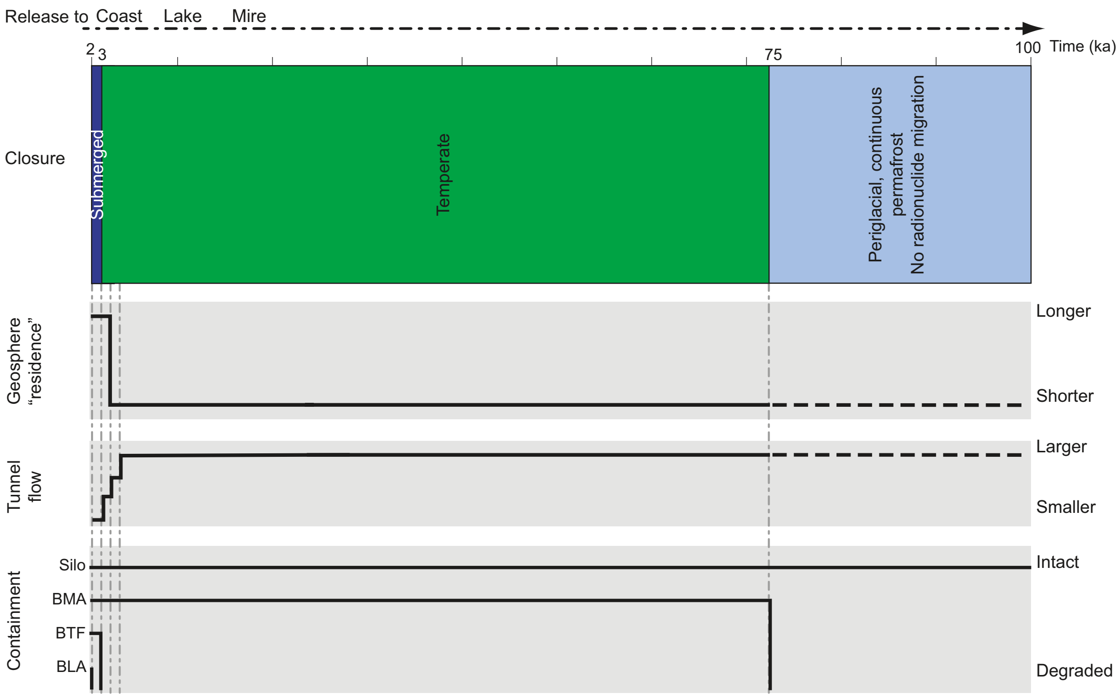


Figure 8-20. Summary of the main scenario's greenhouse variant. Modified from /Thomson et al. 2008a/.

Near-field

The barriers are expected to have a longer life due to the fact that the periods with a colder climate are postponed. The performance of the BMA barriers is expected to be weakened in conjunction with the first deep permafrost around 75,000 AD, whereas the silo's bentonite barriers will remain intact during the entire period studied. The plugs in the tunnels are also assumed to remain intact during the period.

Geosphere

In the geosphere the saline groundwater becomes non-saline in 1,000 years. Due to the long initial temperate period the groundwater will remain non-saline for the rest of the period, since the repository will only be below sea level initially.

Surface ecosystems

Table 8-14 shows what type of ecosystem releases are assumed to occur to at different times, based on the expected evolution of surface ecosystems. The evolution is affected above all by shoreline displacement.

8.4.3 Earthquake

This calculation case is described by a simplified model that overestimates the consequence of an earthquake. For example, sorption and diffusion of radionuclides in the repository and transport in the geosphere are disregarded.

Only one risk contribution is calculated for this calculation case, and dose consequences are not reported separately. The following methodology has been applied, see scenario description in Chapter 7:

1) Since no studies of the repository's ability to withstand earthquakes have been conducted, the analysis is based on an earlier study of earthquake-induced damage /Bäckblom and Munier 2002/. Based on this analysis it is assumed that the facility should be able to withstand an earthquake up to a magnitude of 5, see Chapter 7.
2) By assuming that the radionuclide inventory leaves the repository with the average flux rate which the water in the repository has if the barriers have been breached, the release rate from a breached repository can be calculated. Since radionuclides can nevertheless be assumed to sorb and the repository's pore network cannot be assumed to be interconnected, this is a pessimistic assumption. If this pessimistic assumption is then combined with probability distributions for earthquakes in the Forsmark area /Böðvarsson et al. 2006/, Chapter 7, the radiological risk for different biosphere types can be calculated as a function of the magnitude of the quake.
3) No transport resistance is assumed in the geosphere; the radionuclides are spread directly in the biosphere object that is assumed to be relevant on the basis of the reference evolution.

Table 8-14. Summary of different periods and relevant ecosystem for the main scenario's greenhouse variant.

Time (thousands of years)	Release is assumed to occur to
2–5	Coast
5–7	Lake
7–75	Mire
75–100	No release to biosphere, permafrost.

The effect of glacially induced earthquakes is not included in the earthquake analysis, since damage to the barriers after a glaciation is assumed to be so great that no post-glaciation barrier function is assumed in the reference evolution.

Hydrogeological consequence of an earthquake

The hydrogeological consequences of breached barriers (the flow through the repository resulting from a breached barrier) were studied for different parts of the repository in the SAFE project /Holmén and Stigsson 2001a/ . By knowing the total pore volume in each repository part, the retention time for the water stored in the system can be calculated (observe, however, that the entire pore network is not interconnected, so that the total retention time is probably much longer than the one obtained from this simplified analysis).

Silo repository

In the hydrogeological simulations performed in the SAFE project /Holmén and Stigsson 2001a, section 14.3/, it was assumed that the low-permeable parts of the silo repository had been breached. It is, however, probable that the bentonite barriers will partially retain their hydraulic barrier properties. The results of these studies revealed total flows through the silo's waste domain on the order of 1 m^3/year.

The total volume of radioactive waste in the silo repository is 13,700 m^3 /Almkvist and Gordon 2007/. If the porosity of the conditioning cement is 0.2 /Lindgren et al. 2001/, the total pore volume in the silo repository is approximately 2,740 m^3. Replacing the water volume stored in the concrete backfill takes around 2,500 years.

If it is instead assumed that the whole silo is sheared off and a concentration boundary condition is assigned to the free surface area, the result, given a diffusivity in the backfill of 0.003 m^2/year /Lindgren et al. 2001/, is an area of a few metres where the concentration is affected. In other words, the retention time for the entire inventory should be greater than 2,500 years in this case.

BMA repository

In the hydrogeological simulations performed in the SAFE project /Holmén and Stigsson 2001a, section 14.4/, it was assumed that the concrete structure in the BMA repository had been breached. The result of these studies revealed total flows through the BMA repository's waste domain on the order of 10 m^3/year.

The total volume of the concrete structures in the BMA repository is 14,000 m^3 /Almkvist and Gordon 2007/. If the porosity of the concrete backfill is 0.2 /Lindgren et al. 2001/, the total pore volume in the BMA repository is 2,800 m^3. Replacing the water volume stored in the concrete backfill takes around 300 years.

8.4.4 Earlier freezing in the Weichselian variant (BMA repository)

The climate evolution is the same as in the main scenario's Weichselian variant, but the BMA repository's barriers burst due to freezing earlier than in the main scenario. This happens at the time of the onset of the first continuous permafrost at around 25,000 AD (in the main scenario's Weichselian variant, degradation occurs in conjunction with the second permafrost period at 44,000 AD). The barriers in the BTF repositories have degraded at an earlier point in time, and the effect on the silo, according to the reference evolution, is limited since it is equipped with a bentonite buffer. It is assumed that no radionuclide transport occurs during periods of continuous permafrost.

8.4.5 Earlier freezing in the Weichselian variant (BMA repository) with talik

The same premises as those described in the calculation case "Earlier freezing in the Weichselian variant (BMA repository)", but radionuclide transport takes place during periods of continuous permafrost due to the occurrence of unfrozen zones known as taliks. It is assumed that radionuclides are released to a lake during these periods.

8.4.6 Extreme permafrost

In the permafrost scenario, the air temperature is assumed to be the same as in the reference evolution. The difference is that the climate is too dry to favour ice formation. The climate evolution contains periods of temperate climate alternating with permafrost until 43,000 AD, when a long period of permafrost sets in at repository depth. Figure 8-21 illustrates the expected climate evolution of the permafrost variant during the next 100,000 years. Table 8-15 summarizes the different climate domains in chronological order plus the flow factors used in the calculations. It is assumed that no radionuclide transport occurs during periods of continuous permafrost.

The calculation case "Extreme permafrost" is summarized in Figure 8-22.

Table 8-15. Summary of the climate domains and flow factors from long-term hydrogeological modelling studies for the calculation case "Extreme permafrost" /Holmén and Stigsson 2001a, 2001b, Vidstrand et al. 2007/.

Climate domain	Time (thousands of years)	Comment
Temperate	2–10	Flow factor 1.
Periglacial, continuous permafrost	10–17	Flow factor 0 for the calculation case "Extreme permafrost" when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere.
		Flow factor 10 for the calculation case "Extreme permafrost with talik".
Temperate	17–22	Flow factor 1.
Periglacial, continuous permafrost	22–39	Flow factor 0 for the calculation case "Extreme permafrost" when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere.
		Flow factor 10 for the calculation case "Extreme permafrost with talik".
Temperate	39–43	Flow factor 1.
Periglacial, continuously permafrost	43–100	Flow factor 0 for the calculation case "Extreme permafrost" when the system is assumed to be frozen and no radionuclide transport takes place in the near-field or the geosphere.
		Flow factor 10 for the calculation case "Extreme permafrost with talik".

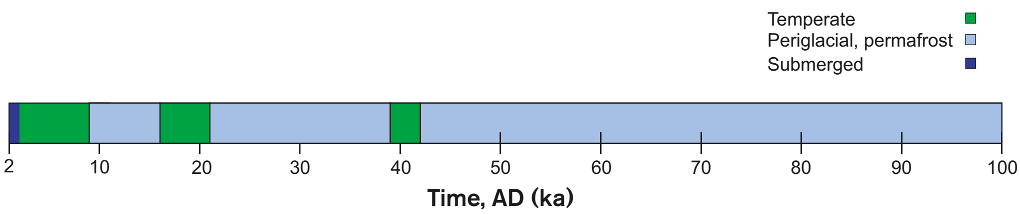


Figure 8-21. *The climate evolution for the calculation case "Extreme permafrost" /Vidstrand et al. 2007/.*

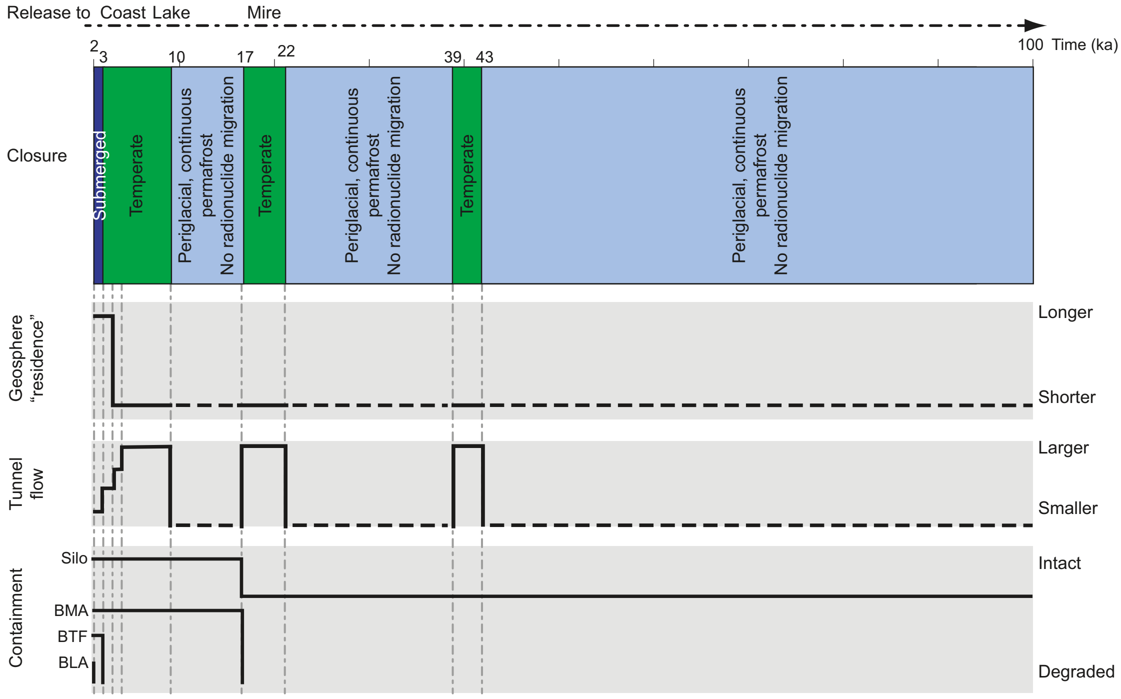


Figure 8-22. *Summary of the calculation case "Extreme permafrost". Modified from /Thomson et al. 2008a/.*

The calculation case follows the main scenario but deviates on the following points:

- Degradation of the BMA repository's barriers is assumed to occur in conjunction with the second permafrost period at 22,000 AD.
- Degradation of the concrete structure in the silo is assumed to occur at 22,000 AD.
- The bentonite in the silo and the tunnel plugs is assumed to remain intact during the entire period.
- The groundwater shifts from saline to non-saline in 1,000 years and then remains non-saline.

8.4.7 Extreme permafrost with talik

The same premises as those described in the calculation case "Extreme permafrost", but radionuclide transport can take place during periods of continuous permafrost due to the occurrence of taliks (unfrozen zones). It is assumed that radionuclides are released to a lake during these periods.

8.4.8 Talik

The climate evolution is assumed to be the same as in the main scenario's Weichselian variant, but unfrozen zones, taliks, occur during periods of continuous permafrost. The groundwater in the repository and in parts of the geosphere between the repository and the ground surface remain unfrozen and radionuclide transport therefore occurs. A talik during the permafrost periods increases the flow 10 times compared with the flow during periods with temperate conditions /Holmén and Stigsson 2001b, 2001a, Vidstrand et al. 2007/, see Table 8-4. It is assumed that radionuclides are released to a lake during these periods.

8.4.9 High concentrations of complexing agents

This calculation case is based on the main scenario's Weichselian variant, but with higher levels of complexing agents in the near-field. High concentrations of complexing agents reduce the sorption coefficients in the near-field and affect the elements that are sensitive to the concentration of complexing agents.

Increased concentrations of the complexing agent isosaccharinic acid (ISA) lead to lower sorption coefficients. It is assumed in the calculation case that the concentration of ISA is 0.01 M. Sorption reduction factors have been used to illustrate the change in the sorption properties of the nuclides. These factors are summarized in Table 8-16 for concrete, gravel and bentonite. It is above all in concrete that sorption is reduced. Tri- and tetravalent actinides are particularly sensitive to complexing agents, especially Pu, which has a sorption reduction factor of 1,000 in concrete, gravel and bentonite alike.

Two calculation cases are generated for the scenario "High concentrations of complexing agents" in Chapter 7: one where cellulose is rapidly degraded, which generates ISA early in the repository, and one where cellulose is assumed to degrade slowly. The results of the main scenario show that a dose peak occurs early, at around 5,000 AD. For this reason, only the case where cellulose is degraded rapidly has been considered.

8.4.10 Gas-driven advection

The calculation case considers the consequences of radionuclide releases from the silo as a result of expulsion of water due to gas evolution.

In order for gas to get out of the water-filled silo, pore water must be expelled. The gas is driven upward through the silo and out through the lid. In order for the gas to escape from the silo through the sand/bentonite layer on top of the silo lid, a pressure of about 15 kPa has to be built up /Pusch and Hökmark 1987/.

Table 8-16. Sorption reduction factors for the calculation case "High concentrations of complexing agents" /Thomson et al. 2008a/.

	Concrete and cement	Sand and gravel	Bentonite
H	1	1	1
C org	1	1	1
C inorg	10	10	10
Cl	1	1	1
Co	10	1	1
Ni	10	1	1
Se	1	1	1
Sr	10	1	1
Mo	30	1	1
Nb	1	1	1
Tc	10	10	10
Ag	10	1	1
Sn	10	1	1
I	1	1	1
Cs	10	1	1
Ho	1,000	5	5
Np	10	10	10
Pu	1,000	1,000	1,000
Am	500	5	5

In a study of gas transport in the SAFE project /Moreno et al. 2001/, it was estimated that 72.5 m^3 of pore water must initially be forced through the silo lid in order to expel water from the gas evacuation pipes and from the sand/bentonite on top of the silo lid. The initial generation of gas is sufficient for this expulsion to occur shortly after closure of the repository. With a pressure in the silo of 15 kPa, the water level in the silo will be lowered 1.5 m at equilibrium, which means that 60 m^3 of pore water will be forced out through the walls and bottom of the silo. Approximately 10 years is required to drive this water volume into the bottom and sides of the silo if the hydraulic conductivity of the concrete is around $1 \cdot 10^{-9}$ m/s.

8.4.11 Wells

The case considers future wells in the discharge area or intrusion wells in the repository. After closure it is possible that knowledge of the repository and its contents will be lost. Due to shoreline displacement, the repository will be located above sea level so that wells can be drilled down into the repository at from about 3,000 AD.

Wells in discharge area

Doses from a release to a well located in the repository's discharge area have been estimated by assuming that the entire release from the geosphere is completely mixed with the water in the well, which is used as drinking water and for irrigation of vegetables. In the calculations of doses from a well, it is assumed that it is situated so that the entire radionuclide release from all rock vaults and silo reaches the well. The radionuclide concentration in the well water was calculated by dividing the radionuclide release by the well yield, which is crucial for the concentration of radionuclides in the water. Data on well yields (arithmetic mean 1.2 m^3/hour) have been obtained from a study of coastal wells /Gentzschein et al. 2006/, see further Table 4-8 and wells in the category ÖM. The incremental increases of flows through the repository parts occurring every thousand years can cause instantaneous peaks in the outflow of certain radionuclides. The peak values last for such short times that the doses calculated from them cannot be used as mean values over 50 years. To compensate for this, annual doses from exposure via well are based on 50-year floating averages.

Intrusion wells

Concentrations in the gravel zone around the repository parts for the main scenario's Weichselian variant have been used as conservative estimates of concentrations of radionuclides in the well water. In this calculation case it is assumed that releases only take place to the drilled well.

8.4.12 Alternative inventory

The inventory in SFR 1 changes during operation, and not until the operation has been concluded will the repository have its final inventory. In this calculation case the final radionuclide inventory has been scaled up so that it amounts to the total quantity for which SFR 1 is licensed, 10^{16} Bq, see Table 6-3b in General Part 1, "Facility design and operation". This means that the inventory in the main scenario is increased by roughly a factor of 7. All other premises are the same as for the main scenario's Weichselian variant.

8.4.13 No sorption in the near-field

The purpose of this and the two following calculation cases is to get an understanding of barrier function. In this calculation case, sorption of radionuclides in the near-field barriers is excluded in the analysis. Otherwise the same premises are posited as in the main scenario's Weichselian variant.

8.4.14 Early degradation of engineered barriers

This calculation case describes a case where the BMA repositories' barrier system is assumed to degrade by 5,000 AD. 5,000 AD has been chosen because it is considered to be the most unfavourable time for barriers to be breached, since radionuclide release is assumed to take place to a lake instead of the coast as previously. Otherwise the same premises are posited as in the main scenario's Weichselian variant.

8.4.15 Loss of barrier function, far-field

This calculation case describes a case where the geosphere is excluded as a barrier in the analysis, which means that no retardation of radionuclides takes place in the geosphere. Otherwise the same premises are posited as in the main scenario's Weichselian variant.

8.4.16 Abandoned unclosed repository

In the calculation case "Abandoned unclosed repository", the radiological effects of abandoning the repository without closure are studied. Such a repository will be filled with salt water with the same salinity as the surrounding sea during a fairly short period of time (a few tens of years). When the repository is filled with water it is assumed that radionuclides are dissolved in the surrounding water, but since the waste in the repository is continuously backfill-grouted the entire radionuclide inventory will not be accessible immediately. It is normally assumed that the different cement barriers in the system are stable (see reference evolution) and are expected to have a useful life of several thousand years, which is also assumed to apply to the backfill grout.

Since the repository's entrance tunnel is near the Baltic Sea, it is not judged likely that a future population would choose to take water from the tunnel entrance if the quality of the water is not better than in the surrounding sea. However, surface runoff could lead to the formation of a fresh-water pool and the use of the entrance as a source of water. For this to happen, however, a halocline must be formed and there must be little mixing between the saline and the non-saline water. This is not unreasonable and could happen, but if it were to happen, mixing between the contaminated saline water and the non-saline water would be limited.

In this example it is assumed that a halocline and a fresh water body are formed and that the knowledge we have today about the radiotoxicity of the repository is lost. The following is assumed in the calculation case:

- The repository is abandoned when the inventory is at its maximum according to Table 8-1. Knowledge of the repository's radiotoxicity is lost and the upper part of the tunnel system is filled with fresh water, so that water from the repository can be used as drinking water. his is assumed in this example to take 100 years, and the water in the system is regarded as being completely mixed.
- The excavated volume in SFR 1 is approximately 400,000 m^3 and the total waste volume is approximately 63,000 m^3, which means that the radionuclide inventory will be dissolved in ~337,000 m^3 of water.
- Based on today's situation, the catchment area from the surface is ~32,500 m^2, which, together with an annual runoff of 130 mm/m^2 (estimated in the site investigation programme for the KBS-3 repository in Forsmark /Berglund 2008/), gives a maximum total annual supply of surface water in the order of 4,000 m^3 and a retention time for water in the repository in the order of hundreds of years.
- The radionuclide dissolution rate will be different in the different repository parts, but is assumed for these calculations to be 2,500 years. During this time, sorption capacity will also be made available at a corresponding rate. There will be various types of material in the system that can sorb radionuclides, for example iron in the repository; bentonite, concrete and cement; sand, gravel, shotcrete and rock. For the sake of simplicity, the K_d values for concrete and cement have been chosen.
- An individual's entire annual water demand, 600 l, is taken from the entrance.

Calculations of the dose consequences for an abandoned unclosed repository were carried out according to the above description, and the results are presented in Chapter 10.

8.5 Combinations of calculation cases

With the method that has been used to arrive at scenarios, no scenario combinations have been identified beyond the ones that are variants of the main scenario.

Since it cannot be said that the less probable scenarios occur independently of each other, we cannot be convinced that a combination of these is less likely than any one of the scenarios that have been combined. On the other hand it is possible, based on the definitions of the scenarios, to say that certain combinations are already covered in existing calculation cases or occur under such different premises (for example late or early in the evolution of the repository) that combinations are not possible.

Combinations of the main scenario and less probable scenarios are not possible, since the less probable scenarios are already variants of the main scenario, except for "Well", which can be combined with all scenarios.

Residual scenarios are defined to exemplify special cases and are not combined with other scenarios.

Combinations with wells

It is assumed in the reference evolution that wells can be drilled directly into the repository or into its discharge area during all periods when the repository is not located under water, when periglacial or glacial conditions prevail, see section 7.6.7. This means that combinations with wells must be included in the calculation of aggregate risk that is carried out in Chapter 10.

Combinations with earthquake scenario

Considering the simplified description of earthquakes in this analysis (the entire inventory is released during the time it takes for inflowing groundwater to replace the water in the repository's pore volume), it is not judged to be relevant to combine this scenario with any other scenario. Since the calculation case does not take sorption into account, a combination with the scenario "High concentrations of complexing agents" is superfluous. Furthermore, the engineered barriers are judged to be breached already, which rules out a combination with the scenarios "Early freezing of the repository" and "Defective engineered barriers". Nor is a combination with high flows, the "Talik" scenario, judged to be necessary since the flow rate assumed in the earthquake scenario is already assumed to be relatively high. Gas-driven advection is judged to be negligible in comparison with the effect of an earthquake, and besides, gas-driven advection is assumed to occur relatively early in the evolution of the repository.

Combinations with "Early freezing of the repository" and "Defective engineered barriers"

The scenarios "Early freezing of the repository" and "Defective engineered barriers" are not judged to be relevant to combine with the scenario "High concentrations of complexing agents". Since the engineered barriers burst due to freezing or otherwise degrade, the calculation premises are judged to have been set so that the consequence of the breached barriers overshadows the consequence of complexing agents in the repository.

Combinations with high flows, the "Talik" scenario, are already included in the scenarios "Early freezing of the repository" and "Defective engineered barriers".

Gas-driven advection, which arises as a result of pressure build-up in the repository, is not combined with cases when the engineered barriers are breached, since intact barriers are a prerequisite for pressure build-up. Based on the reference evolution, most gas production in the silo is expected to occur in the initial phase of the analysis. Thus, a combination with the scenario "Gas-driven advection" would not differ from the scenarios "Early freezing of the repository" or "Defective engineered barriers". Since the radionuclide releases in the scenario "Gas-driven advection" differ little from the main scenario, it is assumed that the radionuclides that have been transported by gas-driven advection in the combination scenario also make little difference to the final result.

Combinations of "Early freezing of the repository" and "Earthquake" are discussed under the heading "Combinations with the earthquake scenario" above.

Combinations with talik

High flows in the repository, the "Talik" scenario, are not combined with the scenario "High concentrations of complexing agents". In the calculation report for the biosphere /Bergström et al. 2008/ it is shown that the "Talik" scenario does not make any significant dose contribution, since the talik comes late in the evolution of the repository (no earlier than 20,000 AD). The nuclide that dominates the dose contribution during the period when radionuclide release occurs to a talik is inorganic C-14. At this point in time, the quantity of inorganic C-14 remaining in the repository can be released during a period of several hundred years without making a significant dose contribution.

Gas-driven advection is not judged to be relevant to combine with the talik scenario, since gas-driven advection is expected to occur early in the evolution of the repository.

Combinations with "Early freezing of the repository", "Defective engineered barriers" and "Earthquake" are discussed above under the headings "Combinations with 'Early freezing of the repository and 'Defective engineered barriers'" and "Combinations with the earthquake scenario".

Combinations with gas-driven advection

Combinations with "Talik", "Early freezing of the repository", "Defective engineered barriers" and "Earthquake" are discussed above under the headings "Combinations with talik", "Combinations with 'Early freezing of the repository and 'Defective engineered barriers'" and "Combinations with the earthquake scenario".

Complexing agents are not expected to be found to any great extent in the silo during the period gas-driven advection is judged to be relevant, see Chapter 6. These two cases are therefore not combined.

9 Radionuclide transport and dose calculations

9.1 Introduction

Chapter 7 presented different scenarios for the evolution of the repository. The scenarios are of importance for studying long-term (post-closure) safety. Calculations of the possible dose are carried out for each scenario. The premises for these calculation cases were briefly presented in Table 8-3, Chapter 8. Detailed accounts can be found in background reports /Avila and Pröhl 2008, Bergström et al. 2008, Thomson et al. 2008a/. This chapter, Chapter 9, presents the results of dose calculations. The calculated doses are used, together with estimated probabilities that the scenarios will occur, to calculate the risk contributions from the repository, which are then compared with the regulatory authorities' risk criterion. This is discussed in Chapter 10.

The calculated individual dose from all of SFR 1 is presented for all calculation cases. A selection of results particularly specifies the contributions from the silo and BMA, due in part to the great importance of these repository parts for the dose from the repository and in part to demonstrate the effect of how the different engineered barriers function. The results for the calculation case "Well in discharge area" are presented together with the other calculation cases. Complete results from all calculation cases for calculated releases of radionuclides from the repository and further transport through the rock are reported in /Thomson et al. 2008a/. Complete results for the doses caused by the releases are given in /Bergström et al. 2008/. Data and other premises are also presented in the background reports. Models used for simulation of release of radionuclides from the repository parts and further transport of radionuclides in the geosphere are presented in /Thomson et al. 2008b/ and described in brief in Chapter 8.

The calculations have been carried out probabilistically for most of the calculation cases, which means that parameter values have been chosen randomly from given statistical distributions and generated via the calculations.

The dose curves in this section exhibit strong peaks and valleys when parameter values change in the transport calculations or at transitions between different biosphere objects. These peaks and valleys are most pronounced when the two factors act in concert. These sudden fluctuations in the doses are an effect of the fact that models or parameter values change with a coarse time resolution. In reality, transitions in the biosphere are gradual over a longer period. For example, the pinching-off of a sea bay to form a lake takes place over a period of 100–200 years, with a continuous reduction of water exchange already in the marine stage. Similarly, the transition from lake to mire takes place continuously over the whole life of the lake. Flow change in the geosphere does not occur instantaneously either, but is linked to the ongoing process of shoreline displacement during the first millennia. But the resolution in data or the complexity of models does not permit these processes to be treated as a more continuous transition in the transport calculations. Instead it is assumed that the groundwater flow through the different parts of the repository changes incrementally every thousand years up to 5,000 AD, in other words up to 3,000 years after closure. All repository parts are assumed to be water-filled immediately after closure in 2040, see /Thomson et al. 2008a/. The residence time for water in the geosphere is also assumed to decrease considerably at 4,000 AD.

Pending the availability of models based on element fluxes and factors based on mechanical models – which are under development within SKB – the same type of radioecological models were used for these calculations as for the SR-Can safety assessment, except for C-14. A specific activity model was used for C-14 /Avila and Pröhl 2008/. It is described briefly in Chapter 8.

9.2 Calculation cases for the main scenario's Weichselian variant

The main scenario describes a possible evolution of the repository and its environs under the influence of expected external conditions. The premises for this main scenario are an inventory of radionuclides corresponding to 50 years' operation of the Swedish nuclear reactors and current known forecasts of nuclear waste from Studsvik and radioactive waste from research and medical activities. The nuclide inventory are listed in Table 8-1. The engineered barriers are expected to function as designed, in other words there may be minor cracks but the barriers are largely expected to be intact for 1,000 years in the case of the concrete tank repositories, 42,000 years in the case of BMA and 56,000 years in the case of the silo. BLA is not credited with any engineered barrier, which means that no retarding/retaining effects are taken into account in the calculations for radionuclides released from BLA. The ongoing process of shoreline displacement influences the hydrological conditions with an increasing groundwater flow and relocation of groundwater discharge areas. Shoreline displacement also leads to changes in the ecosystems above the repository, from the present-day open marine area to an archipelago in which lakes are gradually formed as basins are isolated from the sea. The lakes eventually become filled with sediment. Finally only a few deep lakes remain near Gräsö, while a large part of the area east of SFR 1 has become land.

The climate is based on a repetition of the climate of the last 100,000 years, and the calculation case is called the Weichselian variant.

The influx of radionuclides to the surface ecosystem takes place up to 5,000 AD to a coastal area, subsequently to a lake up to 7,000 AD, and after that to a mire, which is assumed to be rapidly afforested. During the long timespan starting in 44,000 AD when the area above the repository is either ice-covered or under the sea, radionuclide releases take place to a marine area with the same characteristics as the present-day one. It is further assumed that the permafrost conditions are so harsh that land and groundwater freeze so that no transport of groundwater or radionuclides takes place from the repository during these periods, see Chapter 6, section 6.6.

The total calculated dose with contributions from the different repository parts for the calculation case "Weichselian variant" is shown in Figure 9-1. The contribution of the dominant radionuclides to the total dose is shown in Figure 9-2. The numerical uncertainties for the total dose, calculated by the probabilistic methods (see Chapter 8), are shown in Figure 9-3.

The doses are dominated by organic C-14 in the releases from the silo and BMA. The highest dose of 12 μSv per year for release to a sea object occurs around 5,000 AD, with equal shares from the silo and BMA. The inorganic C-14 from 2BTF also makes some contribution to the highest doses. The great importance of organic C-14 is due to the fact that no retardation or retention via sorption on engineered barriers or in the rock of organic C-14 is taken into account in the transport calculations; it is assumed to follow the flow of the groundwater. The maximum dose occurs when the brackish water basin is transformed into a lake as a result of shoreline displacement. At the same time the groundwater flow through the different parts of the repository has increased. The maximum inflow of activity in the form of organic C-14 occurs a thousand years earlier, however /Thomson et al. 2008a/. The release is expected to take place to the brackish water basin, so the doses are lower despite the higher release.

The abrupt transitions in the figures with intervening areas where no dose is shown are due to the assumption that no groundwater flow takes place under permafrost conditions. In reality, such abrupt changes will not occur, since the ecosystems evolve gradually as the climate changes, as demonstrated above. Initially, shoreline displacement causes both a progressive and continuous increase in groundwater flows and, by raising of thresholds, a gradual isolation of basins to form lakes. In reality, the doses cannot decrease to zero, since the concentration of radionuclides in the biosphere will decline gradually.

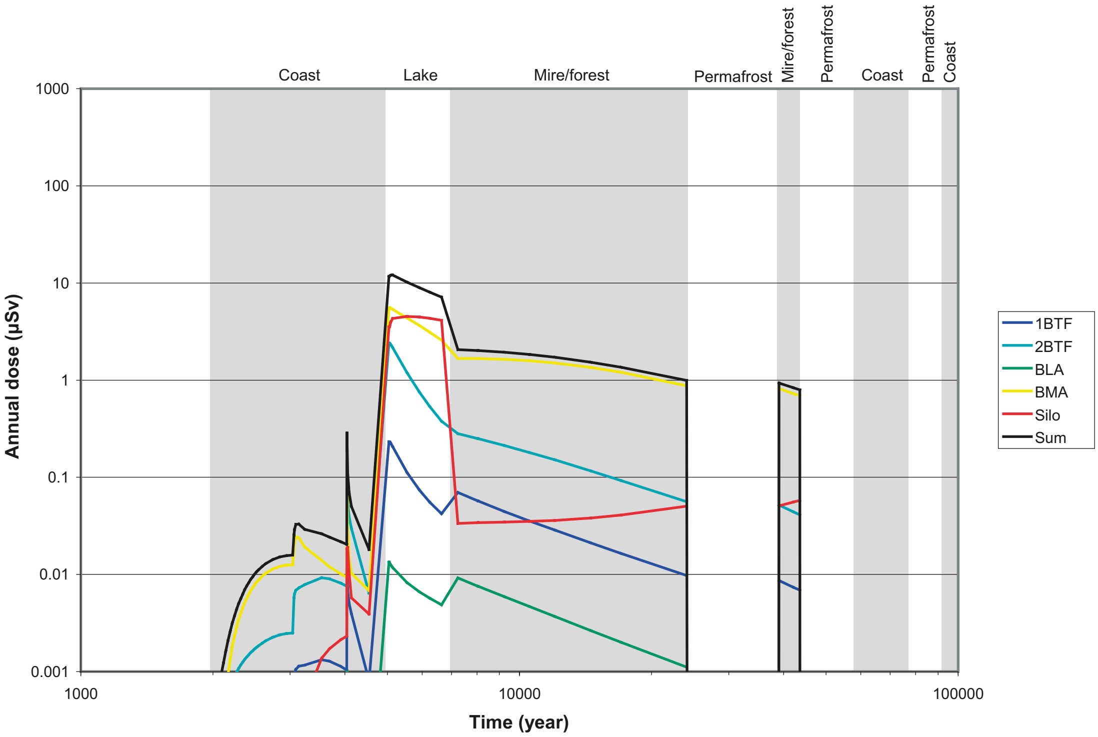


***Figure 9-1.** Arithmetic mean values of annual individual doses from **all of SFR 1 and contributions of the different repository parts to these doses according to the main scenario's Weichselian variant**. Up to 5,000 AD, the coastal ecosystem is the receptor, while between 5,000 AD and 7,000 AD it is the lake ecosystem, and between 7,000 AD and 22,000 AD it is the mire object. This is followed by a period with permafrost before a temperate period is reinstated with the mire object as receptor once again. After 44,000 AD permafrost sets in with an initial glaciation at around 58,000 AD, when the coastal ecosystem returns. Due to the glaciation, the area above the repository is expected to end up beneath the sea, so that the coastal ecosystem once again becomes the receptor of activity releases. Under permafrost conditions there is no groundwater outflow to the surface, and thereby no doses (see section 8.4.1). The upper boundary of the graphs (1,000 µSv) corresponds to the natural background radiation without additional doses from e.g. X-ray examinations. The gradually changing surface ecosystems are shown alternately with a white or grey background and notation of the current ecosystem object. The top part of the figure also shows when permafrost conditions prevail.*

At 7,000 AD, when radionuclides are released to the mire, the doses decline mainly due to the fact that releases of C-14 to a mire give much lower doses than the equivalent activity released to a lake, at the same time as the releases of organic C-14 decrease /Thomson et al. 2008a/. In /Avila and Pröhl 2008/ it is shown that exposure to C-14 released to a terrestrial area gives a much lower dose than the equivalent release to a lake. The dose contribution from release of Cs-135 increases when Cs-135 is released to the mire, which is due to a higher dose from Cs-135 in the forest ecosystem than for the equivalent release to the lake /Bergström et al. 2008/. The mire has been assumed from the exposure viewpoint to be immediately afforested.

The releases from the silo and BMA dominate the maximum dose, while the releases from BMA dominate the long-term dose. 2BTF also makes a contribution to the highest value via release of inorganic C-14. The releases take place to the mire object during the first ten thousand years post-closure, after which it decreases monotonically. In the long time perspective, the relatively mobile and long-lived nuclides Ni-59, I-129 and Cs-135 contribute to the doses, see Figure 9-2. The highest calculated doses for releases from the whole repository, as well as from the individual repository parts, are compiled in Table 9-1 below. It can be seen from the table that organic C-14 makes the highest dose contribution.

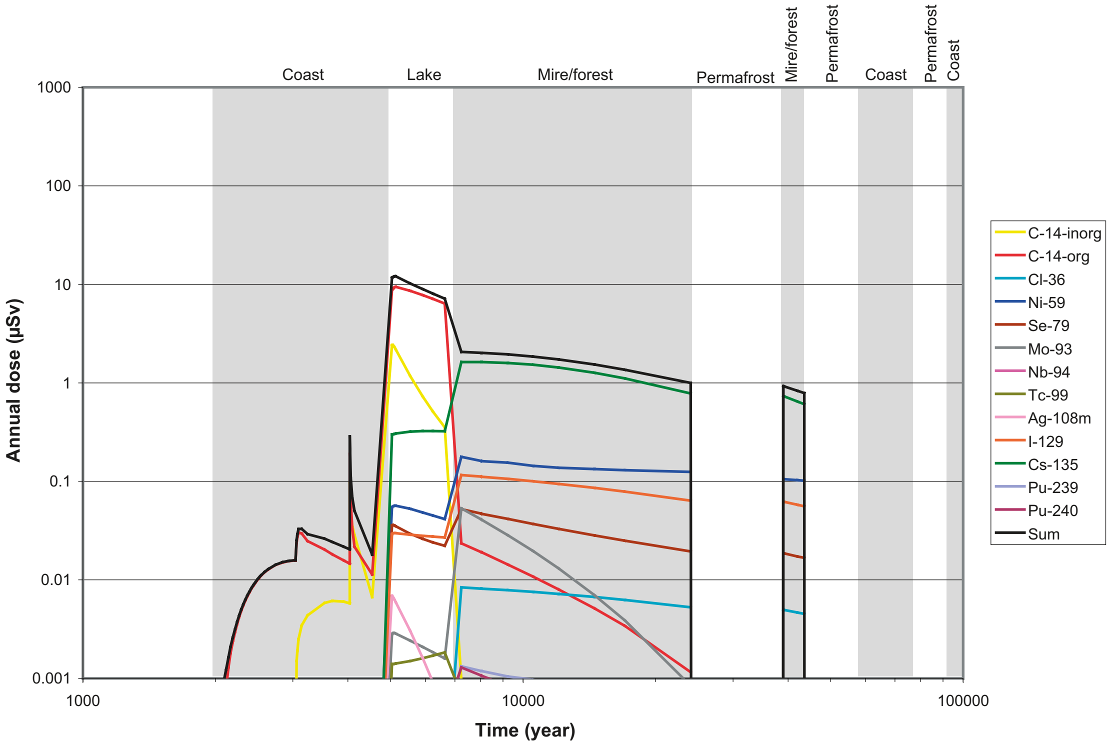


Figure 9-2. *Arithmetic mean values of annual individual dose, both total and per radionuclide expected to make a contribution to the dose from* ***all of SFR 1 according to the main scenario's Weichselian variant****. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

Table 9-1. Highest calculated mean values of annual individual doses from the different repository parts and for all of SFR 1 for the calculation case "Weichselian variant". The dominant nuclides are also given. The highest individual dose occurs around 5,000 AD for all repository parts.

Repository part	Highest individual dose [µSv/year]	Dominant nuclide
Silo	4.5	organic C-14
BMA	5.6	organic C-14
1BTF	0.2	inorganic C-14
2BTF	2.4	inorganic C-14
BLA	0.01	inorganic C-14
Total SFR 1	12	organic C-14

9.2.1 Uncertainty interval

Uncertainties in the calculated doses, due to uncertainties and variations in parameter values, have been studied in the probabilistic calculations. Figure 9-3 shows, as a function of time, the arithmetic mean value, the median value and the 5th and 95th percentiles of the calculated distribution of the total dose from calculated releases from all of SFR 1 according to the main scenario's Weichselian variant. The values were obtained by adding together the corresponding values per repository for all nuclides. For comparison, the deterministic dose curve is also shown, where the "best estimate" has been used for all parameter values. As is evident from Figure 9-3, the calculated distributions are skewed and the arithmetic mean lies above the median.

9.2.2 Silo

Results for the silo are shown in Figure 9-4. As is evident from the figure, the doses are dominated totally by two radionuclides, to begin with by C-14 and then, when inflow takes place to a terrestrial area, by I-129, whose release and dose increase with time. I-129 sorbs in the concrete barriers, in contrast to organic C-14. The total dose at 25,000 AD has increased slightly from 7,000 AD, but the levels are low. The highest dose from I-129 is 0.03 µSv per year, which is less than 1/10,000th of the normal background radiation. The barriers work as designed up to 56,000 AD, effectively preventing any appreciable outflow of radionuclides with more sorbing properties, such as Ni-59, Cs-135 and of course the strongly sorbing actinides. The dose contribution from Cs-135 increases slightly with time due to retardation in the barriers. Mo-93, which is also a relatively mobile radionuclide with a considerably higher dose from the terrestrial area than from the limnic area /Bergström et al. 2008/, contributes 0.005 µSv per year via releases to the mire. The doses from Mo-93 diminish rapidly due to physical decay.

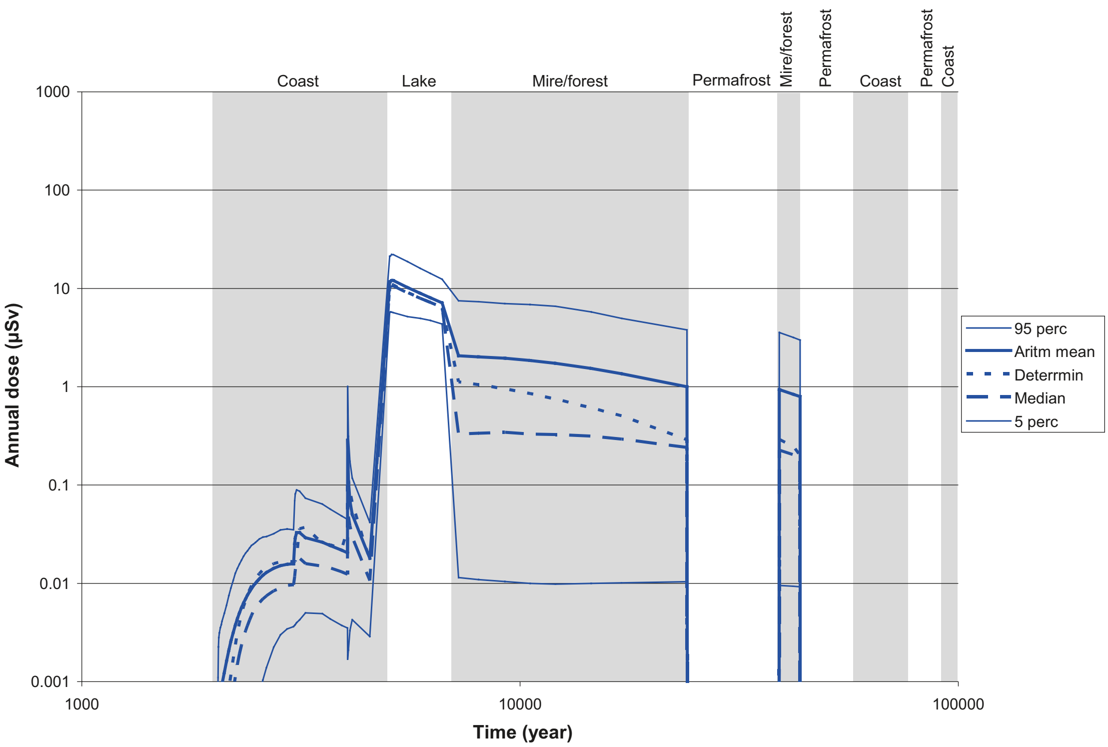


Figure 9-3. *Arithmetic mean, median and 5th and 95th percentile of annual dose distribution for calculated releases from* ***all of SFR 1 according to the main scenario's Weichselian variant****. Deterministically calculated doses are also shown. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which explains the low dose during this period. After 44,000 years there is permafrost, an ice sheet or a situation where the repository area is located under water, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

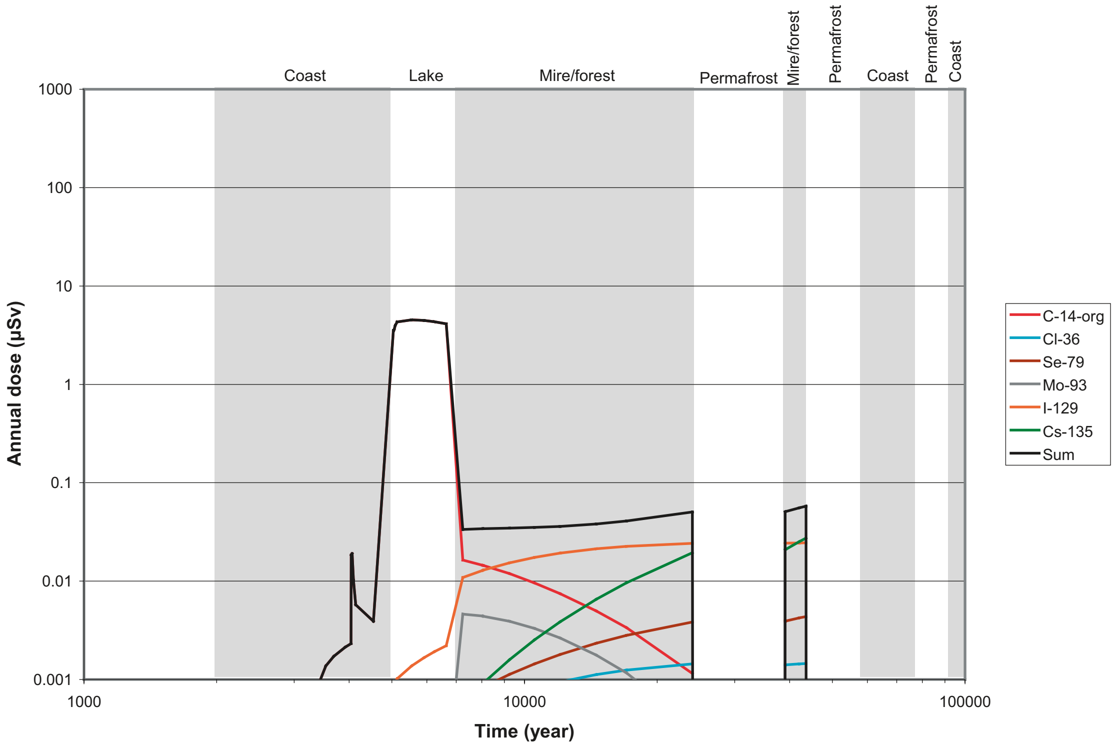


Figure 9-4. *Arithmetic mean values of annual individual doses, total and per nuclide, from calculated releases of radionuclides from* ***the silo according to the main scenario's Weichselian variant****. Results from individual radionuclides that are lower than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

Well in discharge area

Results for dose from a well are shown in Figure 9-5. The assumption is that the well annually receives the activity that has been calculated to be released from the silo. The calculations show that the highest dose occurs early, around 4,000 AD, in conjunction with the increase in flow through the geosphere at that time. Besides organic C-14, Mo-93 and I-129 give doses. The highest dose is 0.9 µSv per year. The contribution from Mo-93 declines rapidly, while the dose from I-129 year increases up to 0.1 µSv per year and reflects the increasing release of I-129 from the silo. No doses for the well case are calculated for the permafrost period from 25,000 AD to 39,000 AD or for times after 44,000 AD, when glaciations, with associated sea level rise, lead to a situation where the area above the repository is either ice-covered or submerged beneath the sea and there are no wells in the area.

9.2.3 BMA

Results for BMA are shown in Figure 9-6. As with the silo, organic C-14 dominates the release and the doses during the first 5,000 years post-closure. The early peaks, when the outflow of radionuclides takes place to a basin in Öregrundsgrepen, are due to (as with the silo) the increased groundwater flows occurring every thousand years assumed in the transport calculations. The highest calculated dose is 5.6 µSv per year, caused by releases of organic C-14 to a lake.

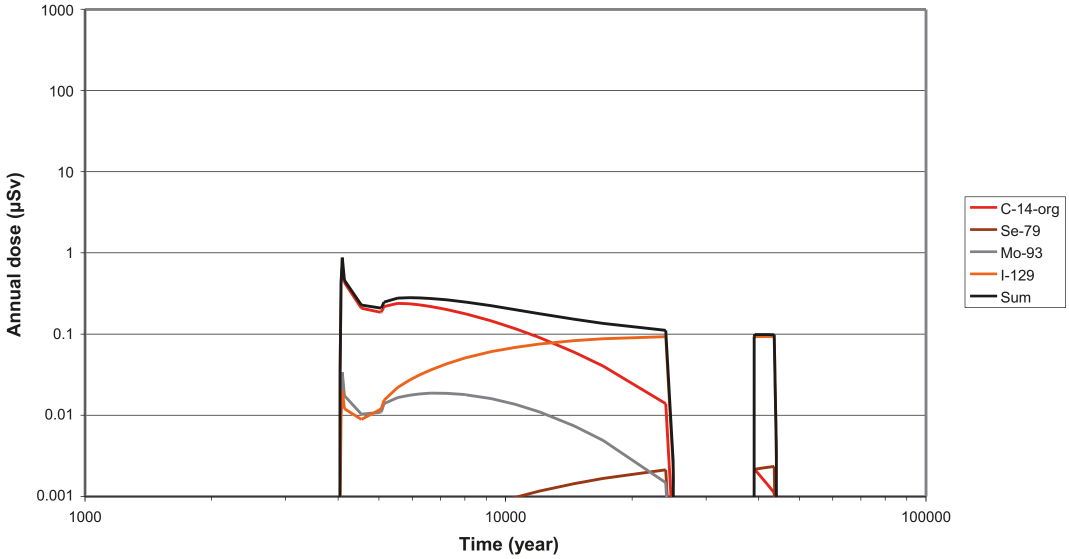


Figure 9-5. *Arithmetic mean values of annual individual dose, both total and per radionuclide, for* ***exposure from a well*** *that has received the annual calculated release from* ***the silo according to the main scenario's Weichselian variant****. The floating average over 50 years is shown, see Chapter 8, section 8.4.11. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

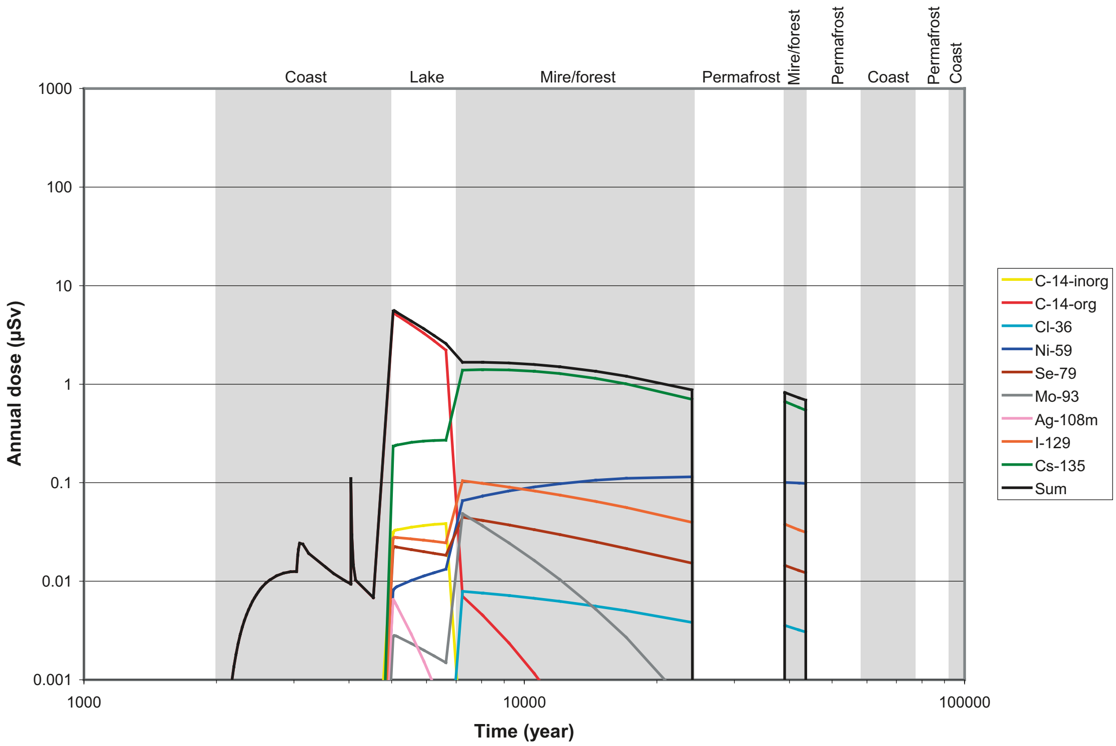


Figure 9-6. *Arithmetic mean values of annual individual doses, total and per nuclide, from calculated releases of radionuclides from* ***BMA according to the main scenario's Weichselian variant****. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

In contrast to the silo, which has thicker cement barriers and a surrounding layer of bentonite mixture and whose barriers are assumed to perform as planned up to 56,000 AD, the transport calculations for BMA show earlier and higher releases of relatively mobile radionuclides such as I-129, Cs-135, Ni-59 and Se-79. Due to its higher inventory in BMA than I-129 and Ni-59, the radionuclide Cs-135 dominates the doses when release takes place to the mire object. The release and the dose from Ni-59 increase with time, however. The doses from I-129 and Cs-135 decline with time, as does the total dose from all radionuclides. In the same way as for the silo, the doses become low, below 0.001 µSv per year and are therefore not visible in the figure for the late times, when glaciation depresses the area below sea level and the releases take place to a coastal ecosystem.

Well in discharge area

Results for dose from a well so situated that it annually receives the activity that is calculated to be released from BMA are shown in Figure 9-7. The highest dose appears immediately and is 5.7 µSv per year, with equal contributions from organic C-14, Mo-93 and I-129. The dose from Ni-59 increases slightly with time, like the doses for release to the surface ecosystem. No doses for the well case are calculated for the permafrost period from 25,000 AD to 39,000 AD or for times after 44,000 AD, when glaciations, with associated sea level rise, lead to a situation where the area above the repository is either ice-covered or submerged beneath the sea and there are no wells in the area.

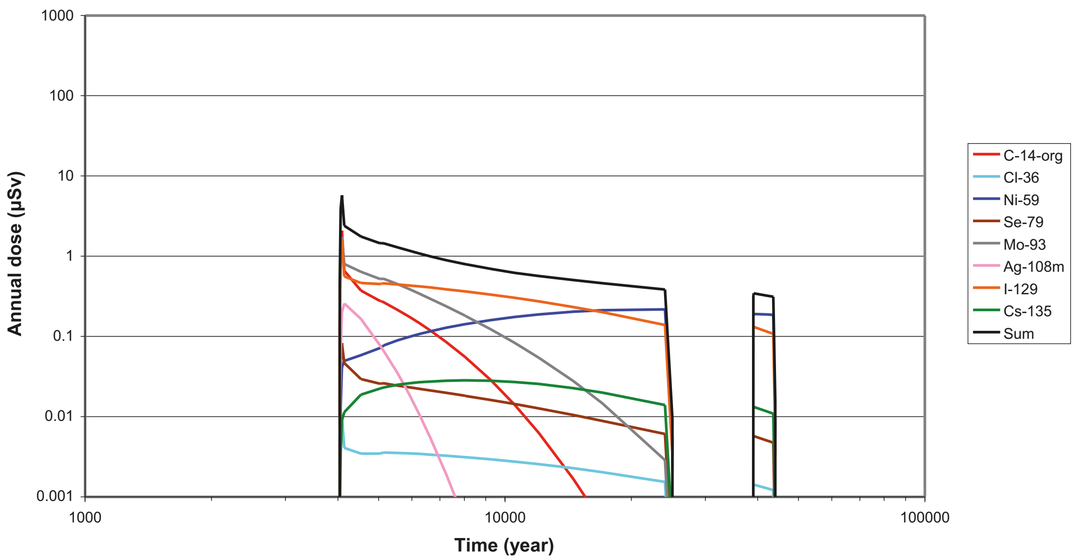


Figure 9-7. *Arithmetic mean values of annual individual doses, both total and per radionuclide, for* ***exposure from a well*** *that has received the annual calculated release from* ***the silo according to the main scenario's Weichselian variant****. The floating average over 50 years is shown. Results from individual radionuclides that are lower than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

9.2.4 1BTF and 2BTF

The results for the concrete tank repositories 1BTF and 2BTF are shown in Figures 9-8 and 9-9. At the time of repository closure, these repository parts together contain approximately 0.6% of the total activity in SFR 1, distributed with 60% higher activity in 2BTF than in 1BTF, see Table 8-1. No retarding or obstructing effects are taken into account for the radionuclides from the concrete in the concrete tanks or the concrete grout, except during the first thousand years post-closure. Thus, the inorganic C-14 that causes the doses after the first thousand years is from 1BTF and 2BTF. The highest doses, approximately 0.2 and 2.4 µSv per year for 1BTF and 2BTF, respectively, therefore reflect the distribution of the inventory of the inorganic C-14 between the two concrete tank repositories. The amount of inorganic C-14 is 7.5 times higher in 2BTF than in 1BTF. The higher inventory of organic C-14 in 2BTF than in 1BTF is also noticeable in the doses, see Figure 9-9. Other nuclides that are important from a dose viewpoint are Cs-135 and Ni-59, in that order. They give a similar appearance of the dose curves in Figures 9-8 and 9-9, but with considerably higher doses from 2BTF than 1BTF. This reflects the relationship between the inventories of Cs-135 in the two repository parts. They differ by a factor of 7, see Table 8-1. The doses decrease monotonically after the highest values that arose from the release of inorganic C-14 to a lake. As with the other repository parts, no short-lived (half-lives <100 years) radionuclides make any noticeable dose contributions (in excess of 0.001 µSv per year).

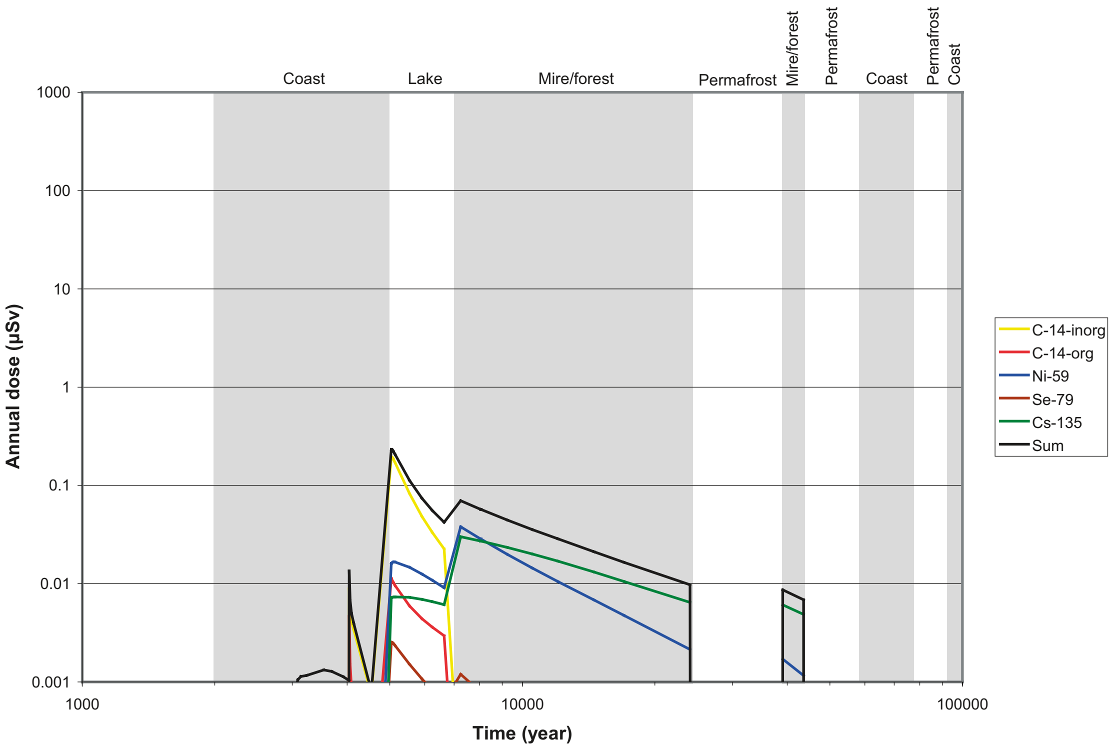


Figure 9-8. *Arithmetic mean values of annual individual doses, total and per nuclide, from calculated releases of radionuclides from* ***1BTF according to the main scenario's Weichselian variant****. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically.. However, the summations include the contributions from all radionuclides. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

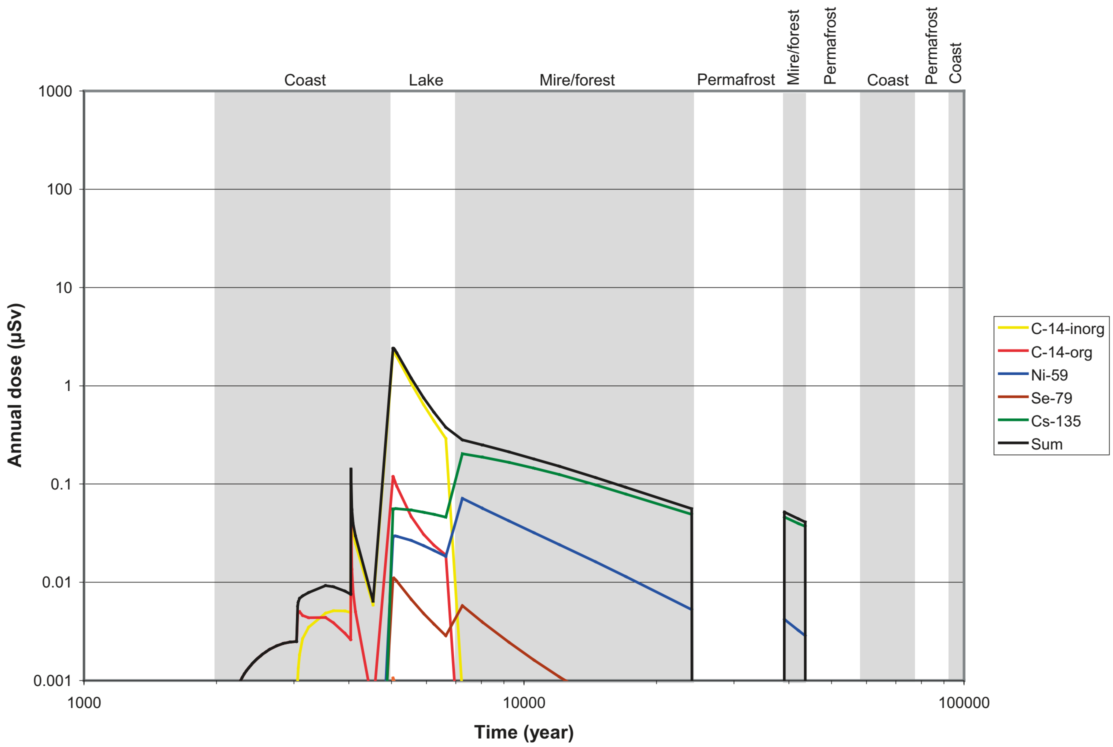


Figure 9-9. *Arithmetic mean values of annual individual doses, total and per nuclide, from calculated releases of radionuclides from* ***2BTF according to the main scenario's Weichselian variant****. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

Well in discharge area

Doses from a well for 1BTF and 2BTF are shown in Figures 9-10 and 9-11. As with other repository parts, it has been assumed that the well annually receives the activity that is calculated to reach the surface ecosystems from the repository parts. The highest doses for exposure from the well are 1.4 and 8.0 µSv per year for 1BTF and 2BTF, respectively. The nuclides that contribute most to the dose are I-129, inorganic C-14 and Mo-93. Organic C-14 also contributes. Around 10,000 AD the doses are dominated by Tc-99 and the actinide nuclides Pu-239 and Pu-240. No doses for the well case are calculated for the permafrost period from 25,000 AD to 39,000 AD or for times after 44,000 AD, when glaciations, with associated sea level rise, lead to a situation where the area above the repository is either ice-covered or submerged beneath the sea and there are no wells in the area.

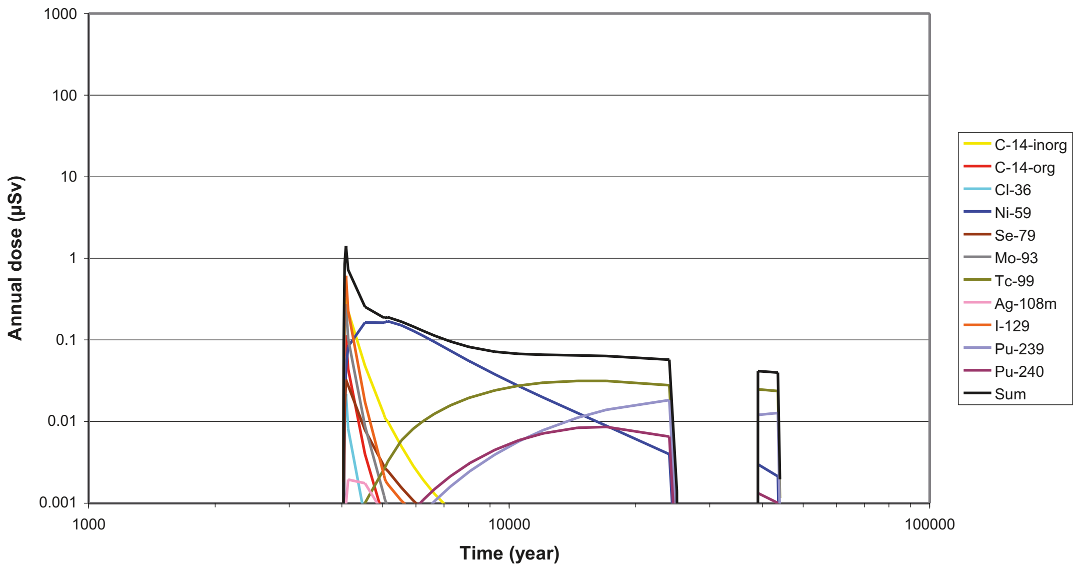


Figure 9-10. *Arithmetic mean values of annual individual doses, both total and per radionuclide, for* ***exposure from a well*** *that has received the annual calculated release from* ***1 BTF according to the main scenario's Weichselian variant****. The floating average over 50 years is shown. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

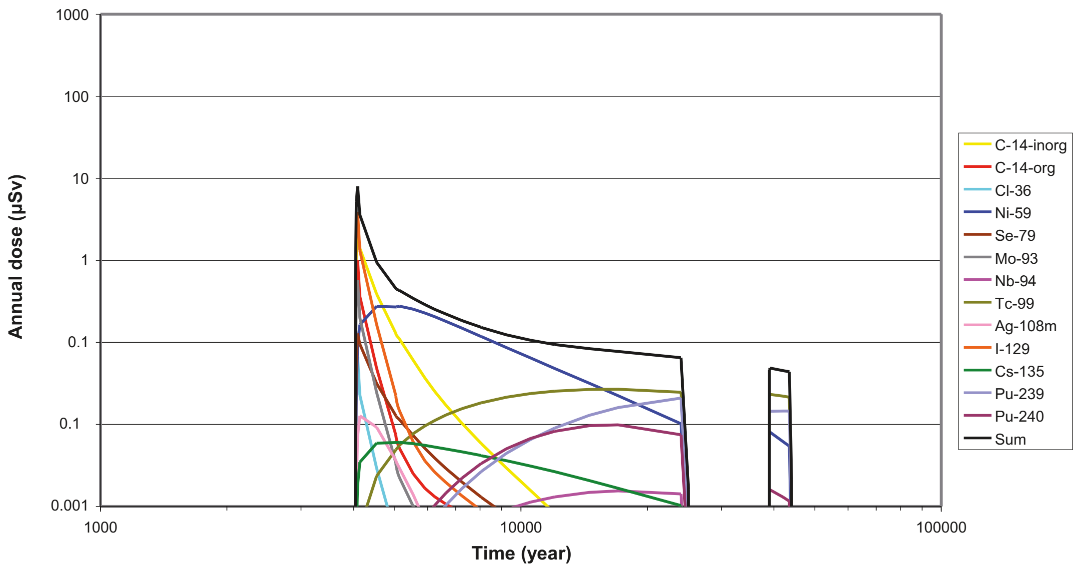


Figure 9-11. *Arithmetic mean values of annual individual doses, both total and per radionuclide, for* ***exposure from a well*** *that has received the annual calculated release from* ***2 BTF according to the main scenario's Weichselian variant****. The floating average over 50 years is shown. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

9.2.5 BLA

Results for BLA are shown in Figure 9-12. Low-level waste, most of which is short-lived, is deposited in BLA. BLA contains about 0.05% of the total activity in SFR 1 at the time of repository closure, see Table 8-1. Two dose peaks can be seen in the calculated release from this repository. First inorganic C-14 causes a highest dose of 0.01 µSv per year, then Ni-59 and Cs-135 cause a second but lower peak when they reach the mire object. BLA is not credited with any barrier function in the transport calculations, which is why releases of Cs-135 and Ni-59 occur earlier than for other repository parts. The highest calculated dose, 0.01 µSv per year, is 1/100,000th of the natural background radiation.

Well in discharge area

Doses for exposure from a well that receives the calculated release from BLA are shown in Figure 9-13. Despite the low inventory of actinides i BLA, their contribution dominates the exposure from a well. This is due to their high radiotoxicity, since they have alpha decay and thereby high values of the dose coefficients. Furthermore, BLA has no engineered barriers. No doses for the well case are calculated for the permafrost period from 25,000 AD to 39,000 AD or for times after 44,000 AD, when glaciations, with associated sea level rise, lead to a situation where the area above the repository is either ice-covered or submerged beneath the sea and there are no wells in the area. The highest dose is 0.5 µSv per year, which is less than 1/1,000th of the natural background radiation.

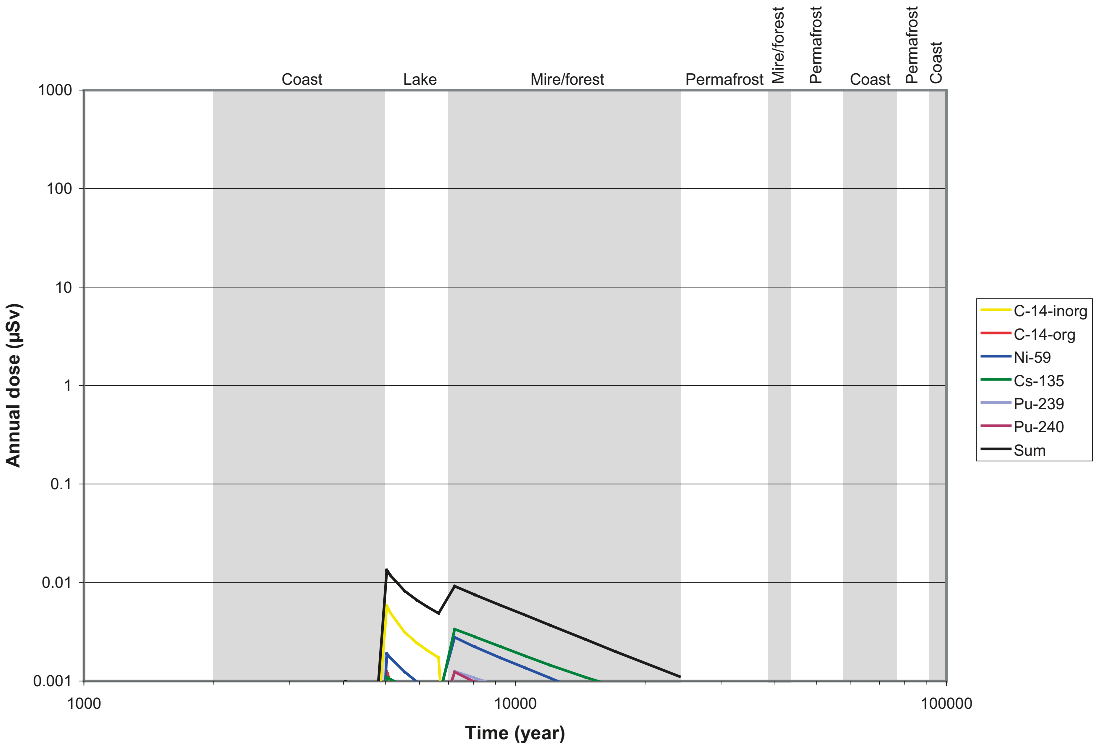


Figure 9-12. *Arithmetic mean values of annual individual doses, total and per nuclide, from calculated releases of radionuclides from **BLA according to the main scenario's Weichselian variant**. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically. However, the summations include the contributions from all radionuclides. For other explanations to the figure, see Figure 9-1.*

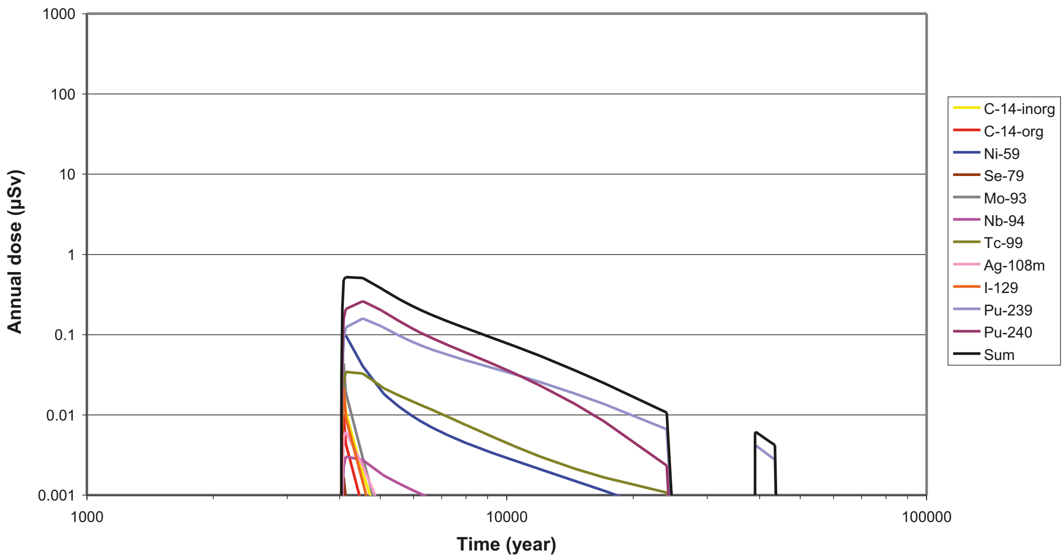


Figure 9-13. *Arithmetic mean values of annual individual doses, both total and per radionuclide, for* ***exposure from a well*** *that has received the annual calculated release from* ***BLA according to the main scenario's Weichselian variant****. The floating average over 50 years is shown. Individual radionuclides contributing less than 0.001 µSv per year are not shown graphically.. However, the summations include the contributions from all radionuclides. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

9.3 Calculation cases for the main scenario's greenhouse variant

The main scenario's greenhouse variant illustrates the doses when a temperate climate is assumed to prevail for a much longer time, up to 75,000 AD, see section 8.4.2. Permafrost conditions set in around 75,000 AD, whereby the last glacial cycle is repeated. The transport calculations for this case were only carried out for the first 70,000 years, which is why the graph only shows results up to around 70,000 AD. Permafrost sets in around 75,000 AD, causing the ground to freeze so that no groundwater flow occurs.

The barriers in BMA and the silo are expected to be intact during the entire temperate period, since the stresses are less than in the Weichselian variant.

Other premises are assumed to be the same as in preceding calculation cases. Thus, the results of this calculation case are not significantly different from those of the previous case. The releases up to the permafrost period are equal in the two cases; the surface ecosystems are also the same, so the doses agree up to around 25,000 AD. The highest doses are reached already around 5,000 AD, after which the doses decrease monotonically. The biggest difference in doses for the two main scenarios is therefore an extension of the exposure in time for the main scenario's greenhouse variant. The Weichselian variant causes marginally higher doses during the late temperate period, due to the fact that BMA's barriers have burst due to freezing.

Well in discharge area

Annual individual doses for wells are shown per repository in Figure 9-15. The figure also shows the sum of the doses from the rock vaults, since releases from them can reach the same well. After an initial peak of 16 µSv per year, the doses decline continuously.

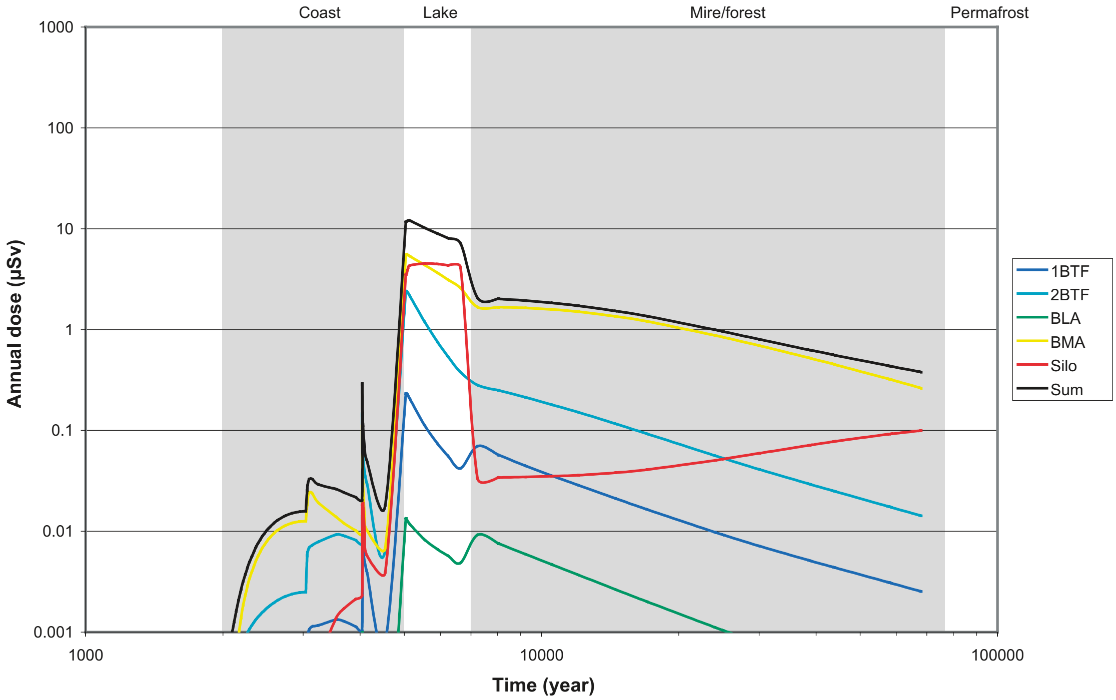


Figure 9-14. *Arithmetic mean values of annual individual doses for* ***all of SFR 1 and contributions of the different repository parts to these doses according to the main scenario's greenhouse variant****. Up to 5,000 AD the coastal ecosystem is the receptor; from 5,000 AD to 7,000 AD it is the lake ecosystem, and from 7,000 AD it is the mire object. This is followed by a period with permafrost and frozen conditions starting in 75,000 AD, which means that no groundwater flow and no radionuclide transport occur. No calculations were made for the period from 70,000 AD. For other explanations to the figure, see Figure 9-1.*

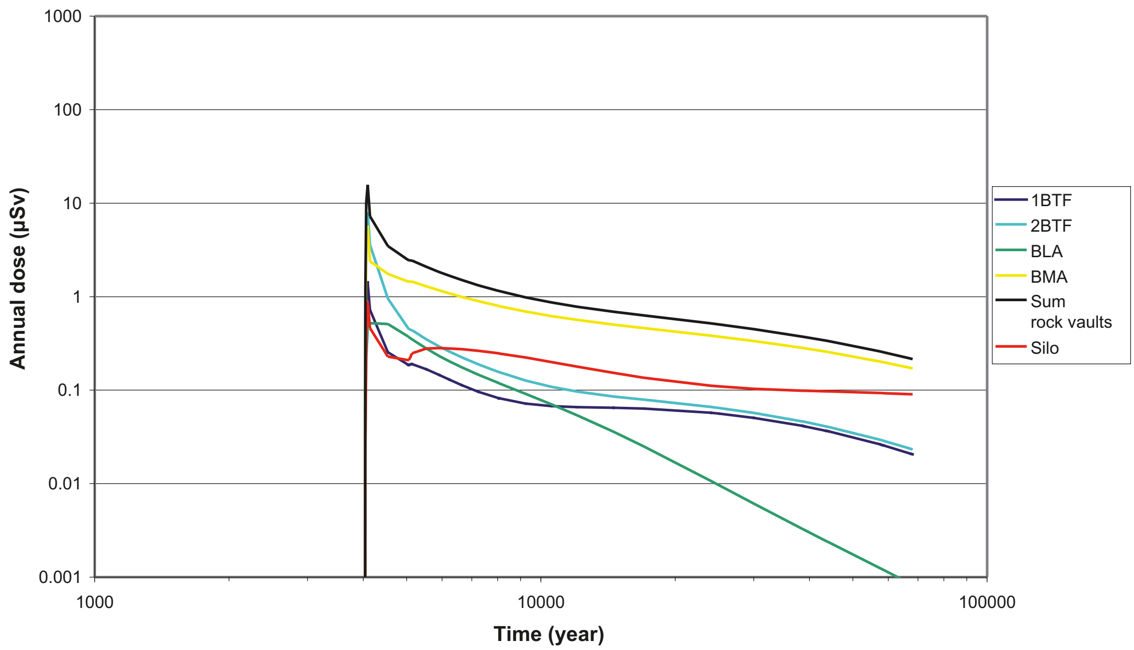


Figure 9-15. *Arithmetic mean values of annual individual doses for* ***exposure from a well*** *that has received all calculated annual releases from the rock vaults for the main scenario's* ***greenhouse variant*** *plus their respective contributions to this dose. The equivalent dose curve is also shown for the silo. The floating average over 50 years is shown. No wells are assumed to exist under permafrost conditions, which is why no doses are calculated after 75,000 AD when permafrost conditions set in.*

9.4 Calculation cases for less probable scenarios

In accordance with /Bergström et al. 2008/, the results presented in this section are concentrated on the silo and BMA, since the results for the other repository parts are affected marginally by the changes made in the premises.

9.4.1 Earthquake

No dose results are reported for the calculation case "Earthquakes"; instead, results in the form of risks are dealt with in Chapter 10. Consequences for the earthquake case are so strongly associated with probability that it is dealt with directly in Chapter 10.

9.4.2 Early freezing in the Weichselian variant (BMA) with and without talik

Two calculation cases are used to illustrate the importance of early freezing of BMA in the main scenario's Weichselian variant. These two calculation cases are included in the scenario "Early freezing of the repository", see Table 8-3. It is assumed that BMA's engineered barriers are breached in conjunction with the first permafrost around 25,000 AD, and the consequences are calculated according to the main scenario's Weichselian variant:

a) no groundwater flow when permafrost conditions prevail,
b) groundwater flow with talik when permafrost conditions prevail.

A talik is assumed in the calculations to give rise to an increased groundwater flow, which drains to a lake. The lake formed by shoreline displacement from the deep trench west of Gräsö is used to illustrate this ecosystem /SKB 2006b/.

The results show that the highest dose for BMA will be about twice that obtained for the main scenario, i.e. 11 µSv per year when no groundwater flow occurs under permafrost conditions (case a) and the mire object receives I-129, Se-79 and Ni-59 from the repository. A lower dose is obtained when the higher groundwater flow with a talik results in a high inflow of organic C-14 to a lake (case b), see Figure 9-16.

Well in discharge area

Annual individual doses for the combination of the calculation case "Early freezing in the Weichselian variant (BMA) without talik" and the calculation case "Well in the discharge area" are shown for BMA in Figure 9-17. The combination "Early freezing in the Weichselian variant (BMA) with talik" and the calculation case "Well in the discharge area" has not been calculated, since this combination always gives a lower dose than the case without a talik (since it is not judged possible for a talik and a well to exist simultaneously).

The results agree with those for the main scenario's Weichselian variant up to and including the first permafrost period, see Figure 9-7. After the first permafrost period, a peak of nearly 17 µSv per year is obtained. This peak is a result of the fact that the concrete barriers in BMA have burst due to freezing during the preceding permafrost period.

9.4.3 Extreme permafrost

Yet another climate variant has been studied with other initial premises as in the main scenario. This variant corresponds to a climate that is cold and dry so that permafrost conditions are favoured, see Chapter 8, section 8.4.6. After the first permafrost period, which sets in around 10,000 AD, a brief period of temperate climate sets in at 17,000 AD and lasts about 5,000 years, after which another, more long-lasting permafrost period begins and prevails up to around 39,000 AD. After a brief temperate period of 4,000 years, permafrost then prevails up to 100,000 AD. Under permafrost conditions, as in the main scenario's Weichselian variant, there is no groundwater flow and consequently no transport of radionuclides. This calculation case is included in the scenario "Early freezing of the repository", see Table 8-3.

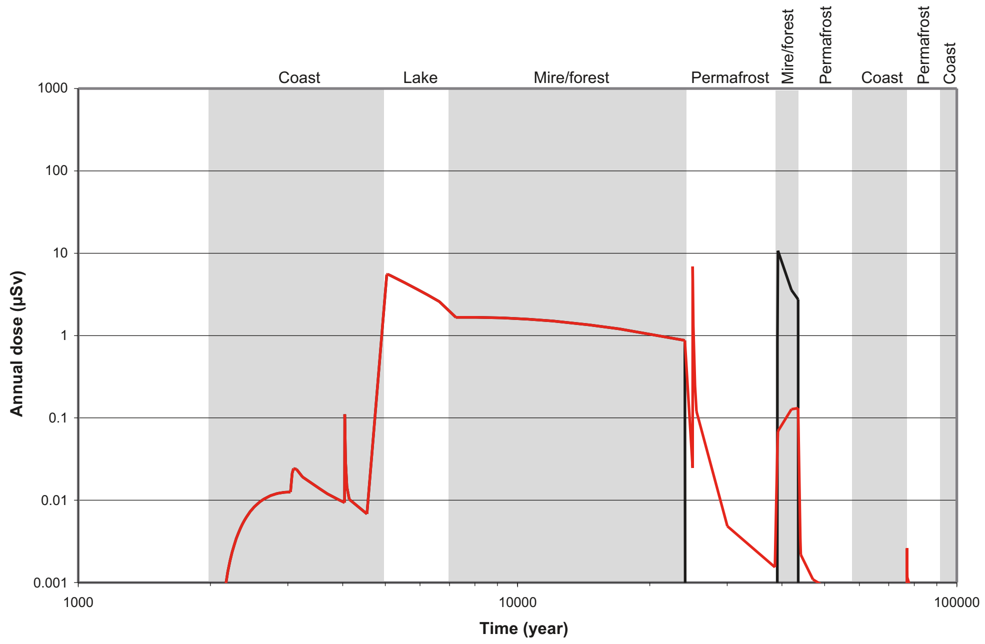


__Figure 9-16.__ Arithmetic mean values of annual individual doses for __Early freezing in the Weichselian variant (BMA repository)__, where the black curve represents doses when there is no groundwater flow during permafrost periods. The red curve shows the doses when a talik is formed during the permafrost period. For other explanations to the figure, see Figure 9-1.

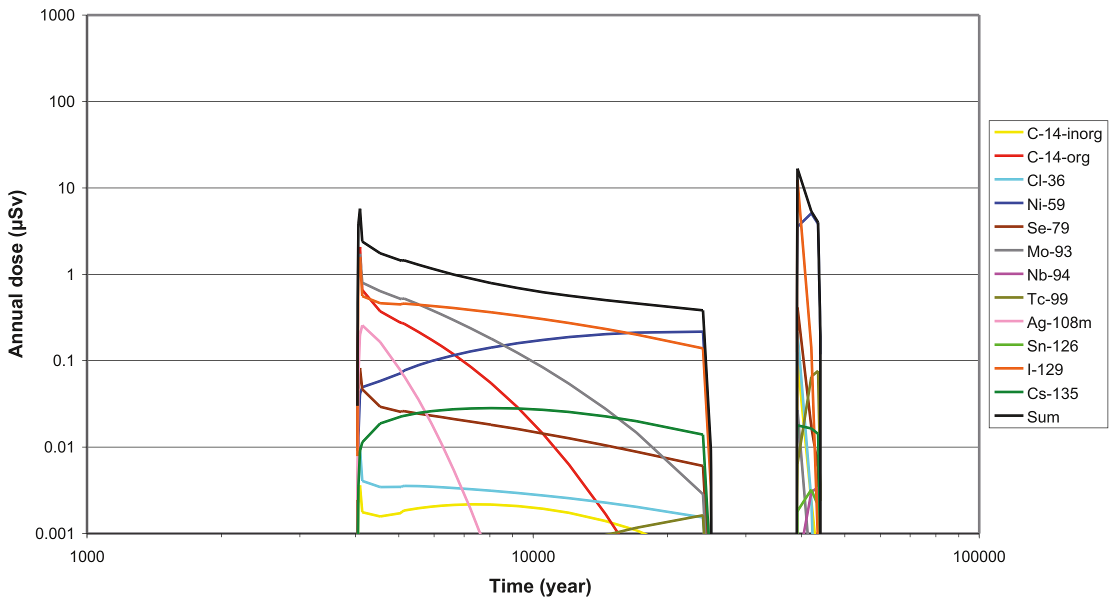


__Figure 9-17.__ Arithmetic mean values of annual individual doses, both total and per radionuclide, for __exposure from a well__ that has received all calculated annual releases from __BMA for "Early freezing in the Weichselian variant without talik"__. The floating average over 50 years is shown. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.

Dose results for SFR 1 are shown in Figure 9-18. During the first several thousand years up to 10,000 AD the doses do not change compared with the results from the main scenario; organic C-14 from the silo and BMA dominate. After this, inorganic C-14 from 2BTF contributes to the highest dose. A marginally higher dose occurs when a temperate period sets in at around 39,000 AD and released radionuclides reach the mire object. The calculated dose peak results from the fact that the barriers in BMA have degraded during the permafrost period.

The late peak is dominated by releases of I-129 from BMA and the silo. It is assumed that the second permafrost period has caused the barriers in BMA and the silo to degrade around 20,000 AD. The bentonite layer around the silo is assumed to be intact, however, which means the release of I-129 from the silo is limited so that the releases from BMA are much higher, despite a lower inventory of I-129 in BMA than in the silo, see Table 8-1.

Well in discharge area

The doses for exposure from a well then show a late peak of 16 µSv per year during the late temperate period. This is mainly due to the fact that BMA's barriers have burst due to freezing, see Figure 9-19.

9.4.4 Extreme permafrost with talik

Another calculation case is a combination of the extreme permafrost that sets in earlier and formation of an unfrozen area, a talik, in the area. This is assumed in the calculations as an increased groundwater flow, which drains to a lake. The same lake is assumed as in the calculation case "Early freezing", see section 9.4.2. The calculation case "Extreme permafrost with talik" is included in the scenario "Early freezing of the repository", see Table 8-3.

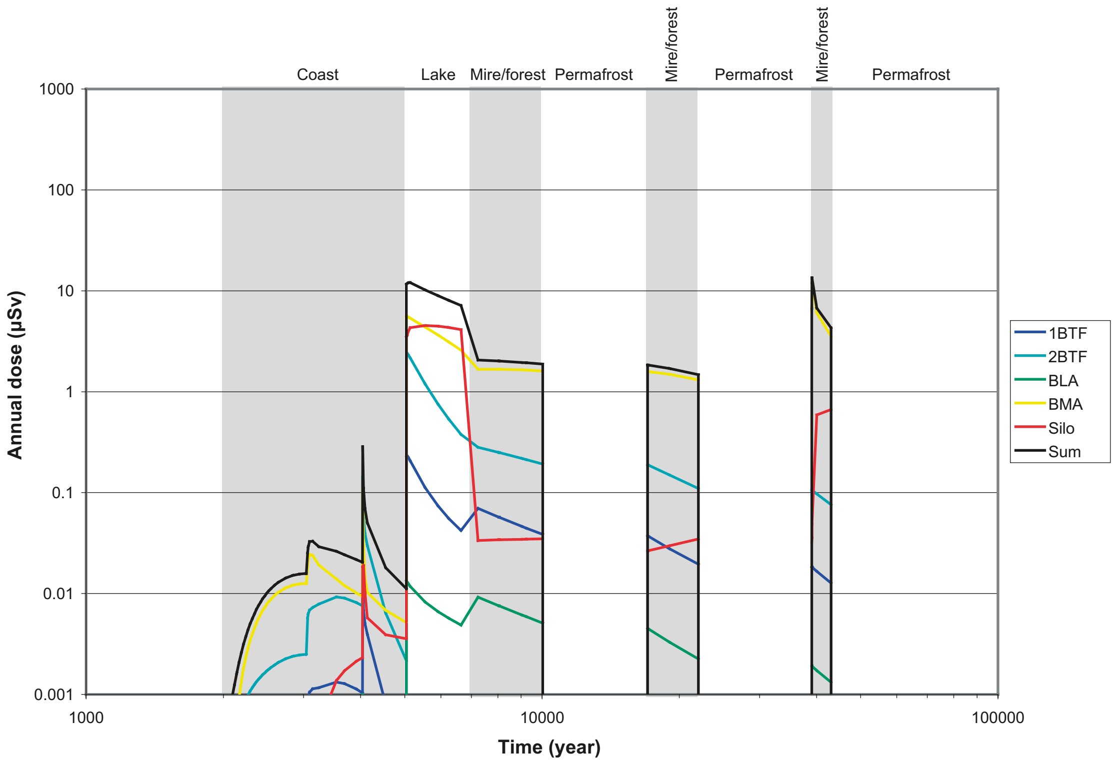


Figure 9-18. *Arithmetic mean values of annual individual doses for* ***all of SFR 1 and contributions of the different repository parts to these doses for the calculation case "Extreme permafrost"****. During the permafrost periods from 10,000 AD to 17,000 AD and from 22,000 AD to 39,000 AD, there is no groundwater flow and thus no transport of radionuclides. Continuous permafrost conditions prevail from 44,000 AD. No doses are calculated to occur during this period. For other explanations to the figure, see Figure 9-1.*

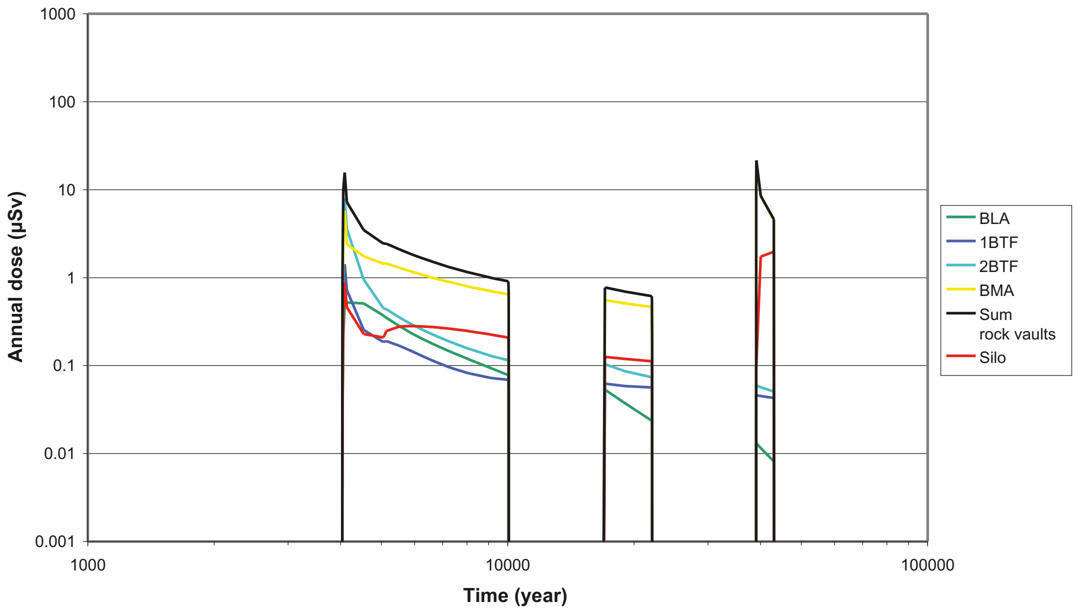


***Figure 9-19.** Arithmetic mean values of annual individual doses for **exposure from a well** that has received all calculated annual releases from the rock vaults **according to the main scenario's calculation case "Extreme permafrost"** plus their respective contributions to this dose. The equivalent dose curve is also shown for the silo. No wells are assumed to exist under permafrost conditions, which is why no doses are calculated from 10,000 AD to 17,000 AD and from 22,000 AD to 39,000 AD, when permafrost conditions are assumed to prevail. After 44,000 AD, permafrost conditions prevail up to 100,000 AD. For other explanations to the figure, see Figure 9-1.*

The calculation case "Extreme permafrost with talik" gives a highest dose of 12 µSv per year from the inflow of organic C-14 to the lake just after 5,000 AD, see Figure 9-20. Three lower peaks in the doses then occur at the transitions between the ecosystems. The first peak around 20,000 AD, about 5 µSv, is due to release of Cs-135 from the silo and BMA. The second peak value, 9 µSv, is caused by inorganic C-14 from BMA. The late peak of 1 µSv per year is mainly due to release of Cs-135 and Ni-59 from the silo to the mire object.

Well in discharge area

Theoretically, the doses from a well would increase if a well could cause exposure in conjunction with a talik, but wells in conjunction with permafrost and talik are not realistic, so no calculations for wells have been performed for these conditions. Doses for exposure from a well in the discharge area will therefore agree with the doses from a well for the calculation case "Extreme permafrost".

9.4.5 Talik

Results have been calculated for a variant of the conditions during permafrost periods. In contrast to the main scenario's Weichselian variant, in which permafrost conditions caused frozen conditions and no flow of water or activity, it is assumed in this case that an unfrozen area, a talik, is formed during permafrost periods. This leads to a high flow of groundwater, which is assumed to drain to a lake corresponding to the last lake formed by shoreline displacement, just west of present-day Gräsö /SKB 2006b/. The lake is assumed to exist during the entire period. The doses as a function of time for all repositories are shown in Figure 9-21.

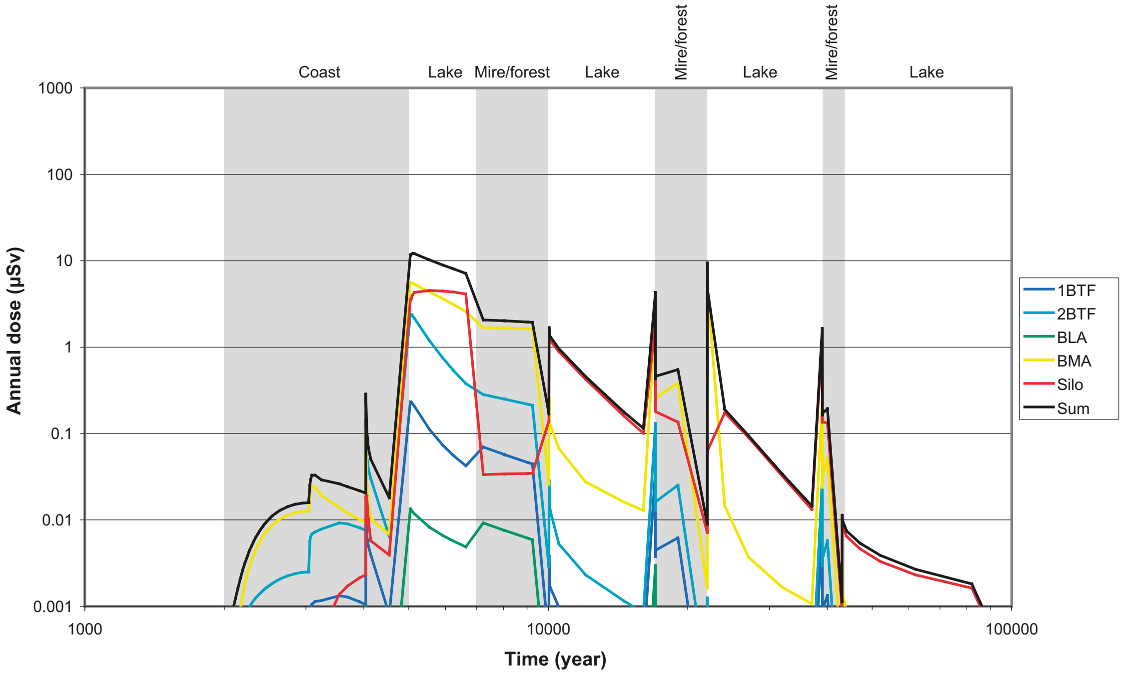


Figure 9-20. Arithmetic mean values of annual individual doses for ***all of SFR 1 and contributions of the different repository parts to these doses for the calculation case "Extreme permafrost with talik"****. In this case, continuous transport of radionuclides takes place with the groundwater since a talik, in the figure labelled as a lake, is formed under permafrost conditions. Note that the lake shown up to 7,000 AD is not the same lake as that used to calculate exposure under talik conditions. For other explanations to the figure, see Figure 9-1.*

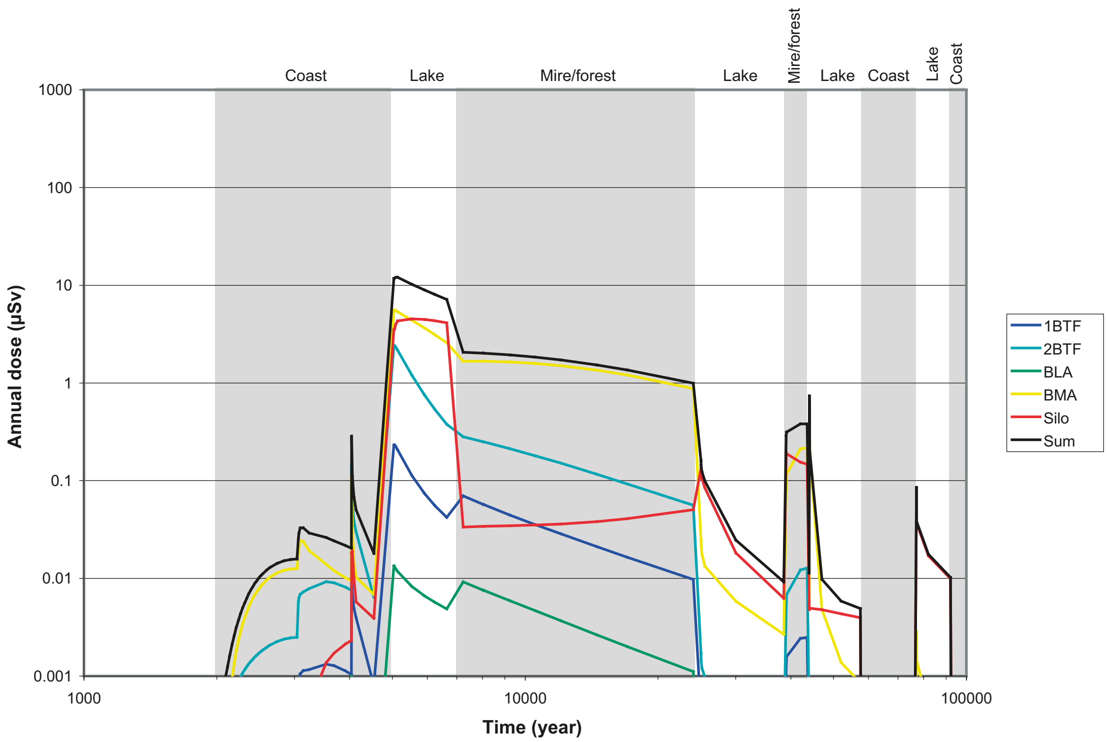


Figure 9-21. Arithmetic mean values of annual individual doses for ***all of SFR 1 and contributions of the different repository parts to these doses for the calculation case "Talik"****. Release takes place to a lake during all permafrost periods. Note, however, that this lake is not the same lake as that used to calculate the dose during the first 5,000 years after repository closure. For other explanations to the figure, see Figure 9-1.*

Mean values of the annual individual doses from SFR 1 and contributions of the different repository parts to these doses are shown in Figure 9-21. The doses up to around 25,000 AD, when permafrost conditions set in, agree with the doses from the main scenario. The contributions to the total dose from the silo and BMA subsequently vary in relation to released radionuclide and ecosystem. Ni-59, I-129 and Cs-135 from BMA dominate the doses for release to the terrestrial area. At the onset of permafrost around 25,000 AD, organic C-14 from the silo dominates the dose via release to a lake. However, this dose is lower than the one caused by the releases of Cs-135 from BMA to the terrestrial ecosystem, see Figure 9-6. The late peak, about 1 μSv per year, appears about 45,000 years post-closure and is due to release of inorganic C-14 from BMA in a sudden pulse when the flow has increased in conjunction with a talik.

Well in discharge area

No additional results for wells are shown since wells do not occur in conjunction with a talik. Doses for exposure from a well therefore agree with the doses calculated for the Weichselian variant up to the onset of the permafrost period.

9.4.6 High concentrations of complexing agents

An increased concentration of complexing agents increases the mobility of certain nuclides such as actinides, whose sorption properties are linked to the concentration of isosaccharinic acid (ISA). The concentration of complexing agents in the near-field is assumed to be substantially higher than is considered to exist in the main scenario. Sorption is therefore reduced by a factor of 0.1 for Ni and Cs and by a thousandth for Pu-239, for example. Releases of radionuclides to the biosphere and doses from them were only calculated deterministically for this case.

For the whole repository, the highest dose is not changed compared with the main scenario's Weichselian variant, since organic C-14 dominates the maximum doses, see Figure 9-22. Organic C-14 is not affected by the presence of complexing agents. The inflow of many radionuclides to the surface ecosystem increases, since sorption in the near-field decreases considerably due to the assumption of the higher concentration of complexing agents.

Well in discharge area

Mean values of the probabilistic calculations were used for calculation of exposure from a well, since these values are considered to be more representative than the deterministic ones. The doses for exposure from a well show an early peak of around 19 μSv per year, see Figure 9-23. The effect of the complexing agents is clearly apparent for BMA, whose maximum dose contribution to the well has nearly doubled compared with the main scenario. At the same time the contribution from 2BTF decreases, due to the fact that the higher mobility leads to an earlier outward transport of radionuclides. The doses calculated for the Weichselian variant are used for BLA, since no sorption is taken into account for release from BLA, and a changed concentration of complexing agents therefore does not affect the results for BLA.

9.4.7 Gas-driven advection

Transport of radionuclides due to gas formation causing advective transport from the silo is not taken into account in the main scenario. In order to shed light on the importance of such transport, releases of radionuclides during a period of increased gas generation were calculated. The result was an early peak of the release of organic C-14 to the coastal area. The dose at the time of the release increased slightly, but the highest dose and the long-term dose were not affected. The case therefore did not lead to any difference in highest dose /Bergström et al. 2008/.

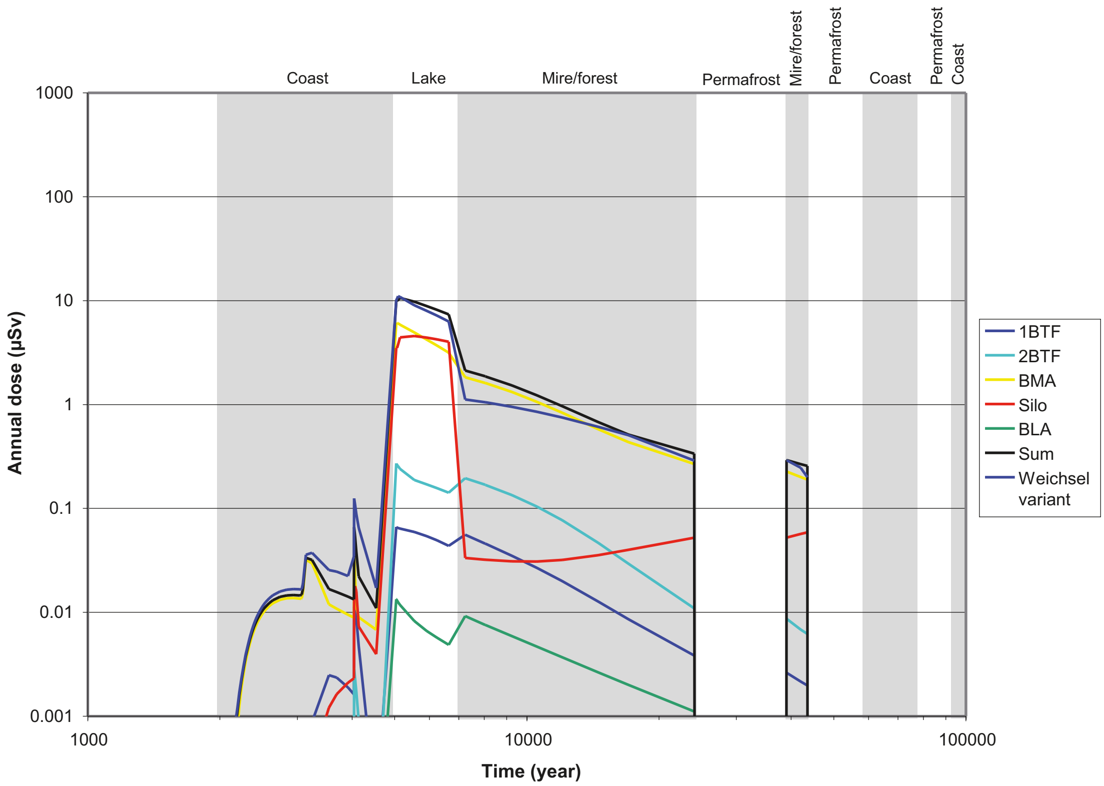


***Figure 9-22.** Annual individual dose for **all of SFR 1 and contributions of the different repository parts to this dose according to the calculation case "High concentrations of complexing agents"**. For comparison, the deterministic results for the main scenario's Weichselian variant are also shown (upper dark blue line). For other explanations to the figure, see Figure 9-1.*

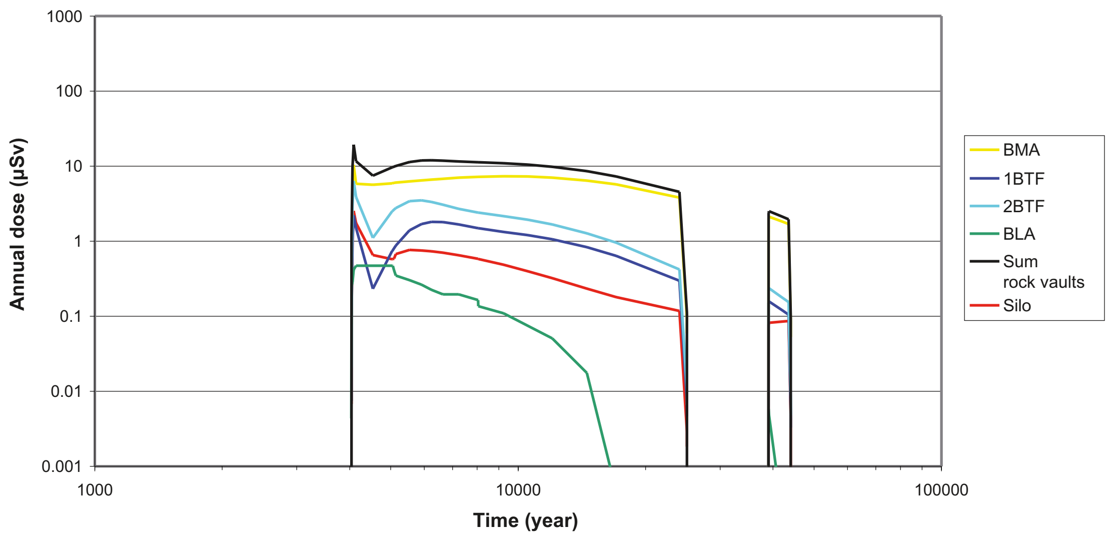


***Figure 9-23.** Total annual individual dose for **exposure from a well** that has received all calculated annual releases from the rock vaults for the calculation case **High concentrations of complexing agents** and their respective contributions to this dose. The equivalent dose curve is also shown for the silo. The results are based on deterministic release calculations as well as arithmetic mean values for exposure from a well. The floating average over 50 years is shown. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

9.4.8 Well in discharge area

The calculation case "Well in discharge area" is included in the scenario "Wells", see Table 8-3. Dose results for exposure from wells in the discharge area have been reported above in the same sections as the doses from the respective calculation cases with inflows of radionuclides to the surface ecosystem. This has been done because these calculation cases give source strengths for calculation of doses from wells in the discharge areas.

9.4.9 Intrusion well in repository

The calculation case "Intrusion well in repository" is included in the scenario "Wells", see Table 8-3. Dose results for "Intrusion well in repository" have been calculated for the calculation cases "Weichselian variant" and "High concentrations of complexing agents".

During the time period for which intrusion wells give a considerable dose in the Weichselian variant, the calculation cases in the scenarios "Main scenario", "Early freezing of the repository" and "Talik" are identical with the Weichselian variant. In the calculation case "Gas-driven advection", a pulse release of radionuclides occurs early, but the release stabilizes at the same level as in the Weichselian variant, before 3,000 AD.

All results presented in this section are based on deterministic calculations.

Weichselian variant

The deterministically calculated doses for the different repository parts are presented in Figures 9-24 to 9-28. The results show that the highest dose is reached in 3,000 AD, which is the first time a drinking water well is judged to be able to be drilled in the repository. The dose then declines relatively rapidly, and after 5,000 AD the dose has declined considerably for all repository parts except the silo. The dose curve declines with time for the silo as well, and at 7,000 AD the dose has fallen to 10% of the highest dose.

2BTF gives the highest calculated individual dose, which amounts to around 1,600 μSv per year.

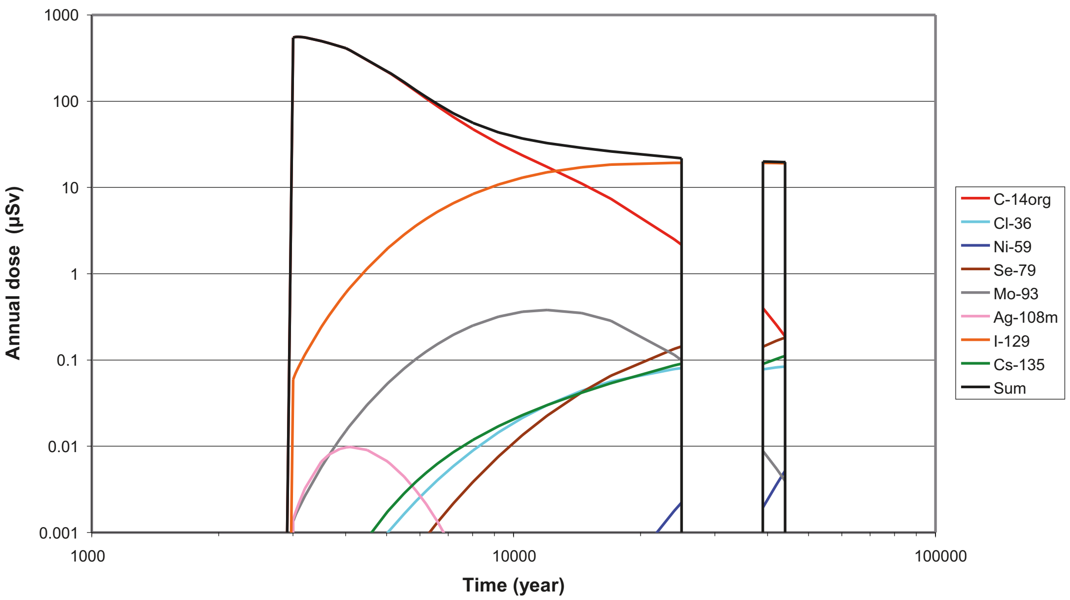


Figure 9-24. Annual individual dose from the calculation case ***"Intrusion well in repository" in combination with the Weichselian variant for the silo****. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

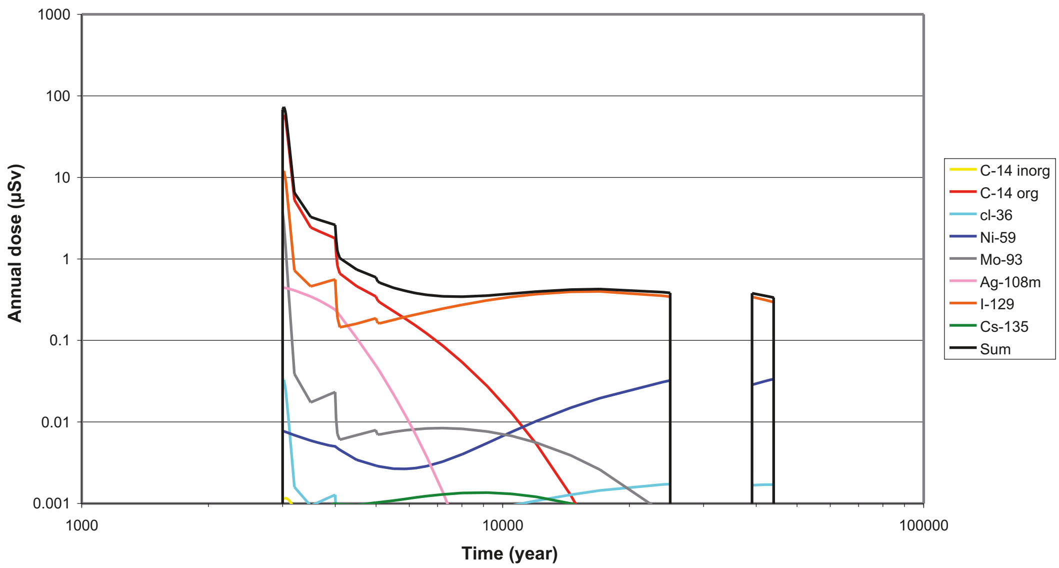


*Figure 9-25. Annual individual dose from the calculation case **"Intrusion well in repository" in combination with the Weichselian variant for BMA**. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

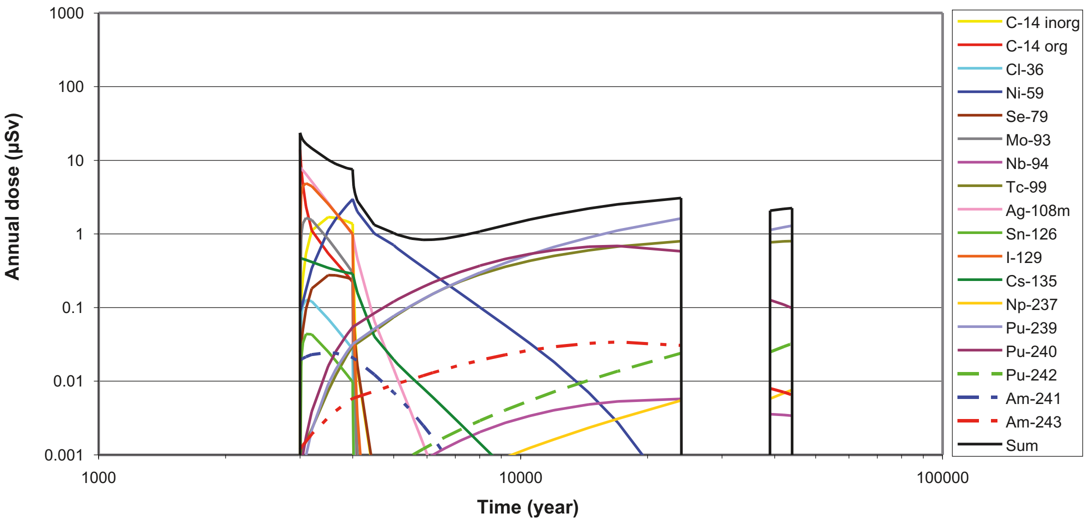


*Figure 9-26. Annual individual dose from the calculation case **"Intrusion well in repository" in combination with the Weichselian variant for 1BTF**. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

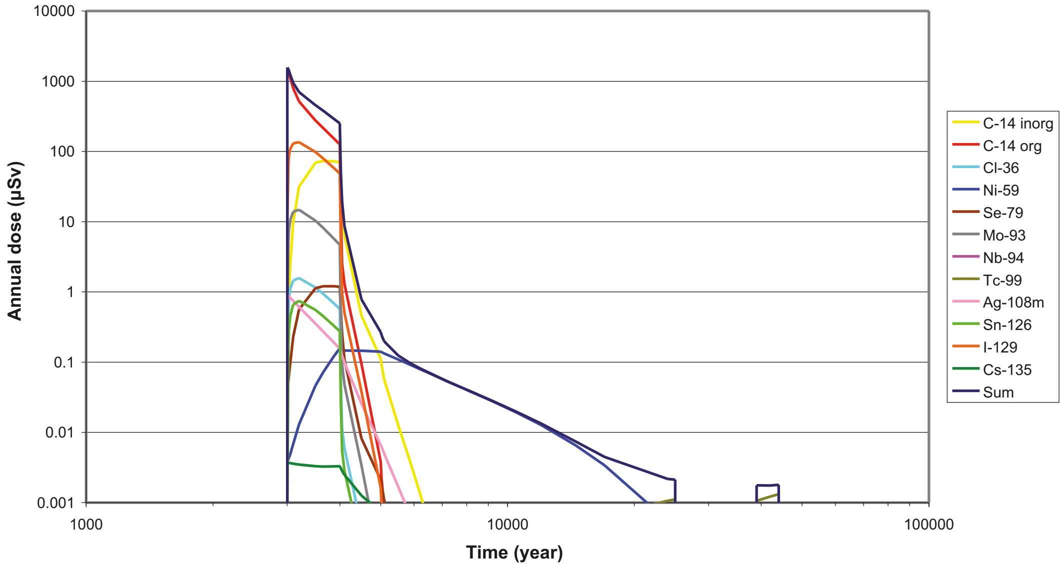


Figure 9-27. *Annual individual dose from the calculation case* ***"Intrusion well in repository" in combination with the Weichselian variant for 2BTF****. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 AD to 39,000 AD) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

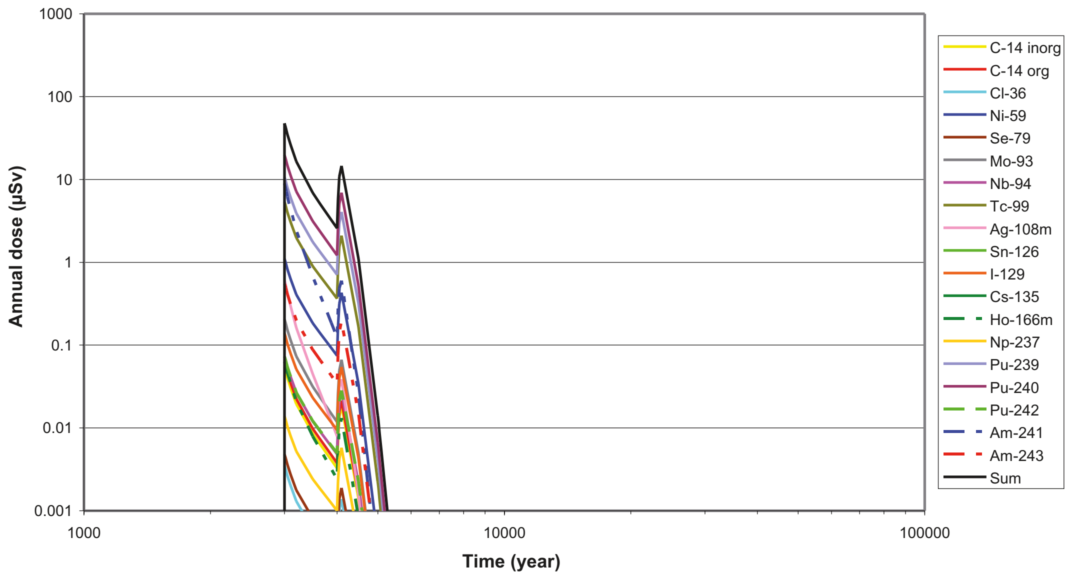


Figure 9-28. *Annual individual dose from the calculation case* ***"Intrusion well in repository" in combination with the Weichselian variant for BLA****.*

High concentrations of complexing agents

Figures 9-29 to 9-32 show the calculated doses from an intrusion well in the different repository parts. As with the results for the Weichselian variant, the highest dose is reached early. Results for BLA are the same in this case with high concentrations of complexing agents as for the Weichselian variant, see Figure 9-28. This is because no sorption is taken into account for BLA, since BLA has no sorption barriers.

The higher mobility caused by the increased concentration of complexing agents increases the doses compared with the Weichselian variant. The highest dose, around 8,500 µSv per year, is given by intrusion in 2BTF. It is the actinides Pu-239 and Pu-240 that give rise to this dose. As with the results for the Weichselian variant, the doses decline with time.

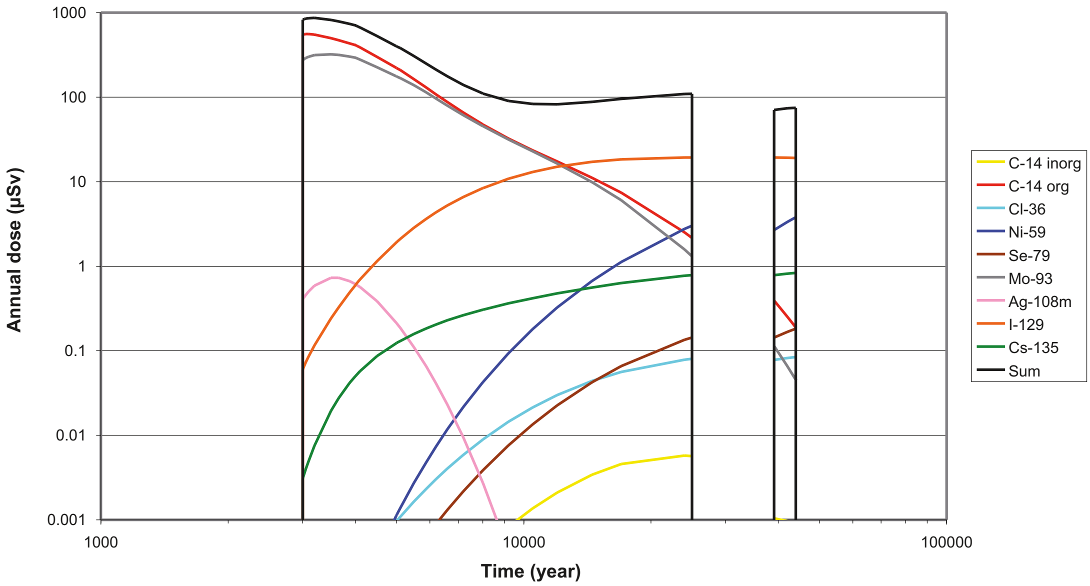


Figure 9-29. *Annual individual dose from the calculation case* ***"Intrusion well in repository" in combination with "High concentrations of complexing agents" for the silo****. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 ad to 39,000 ad) or during periods when the area above the repository is either ice-covered or submerged beneath the sea****.***

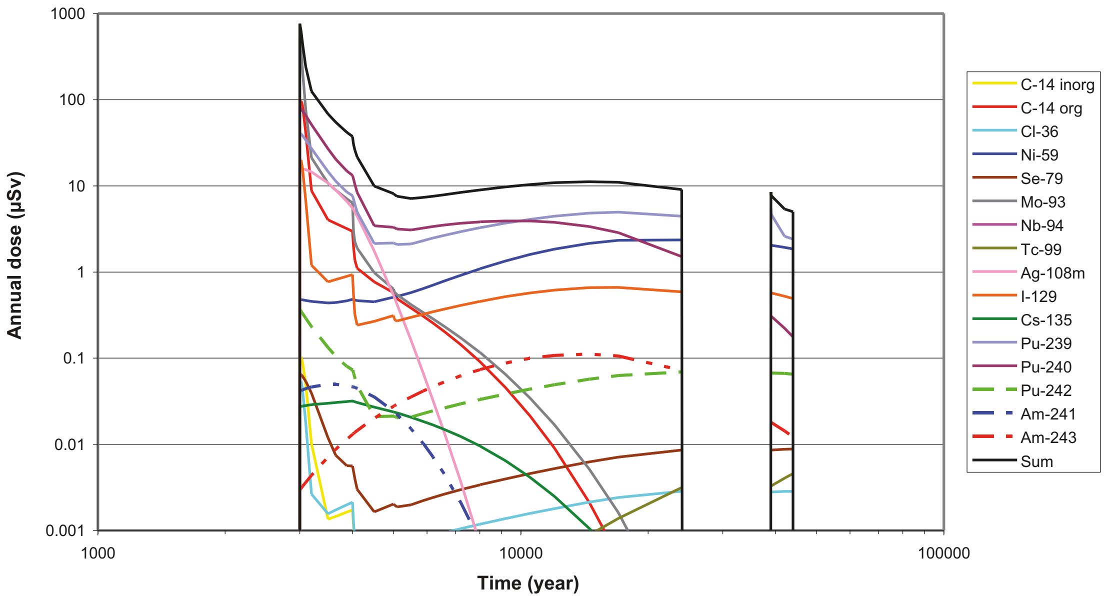


Figure 9-30. *Annual individual dose from the calculation case* ***"Intrusion well in repository" in combination with "High concentrations of complexing agents" for BMA****. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 ad to 39,000 ad) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

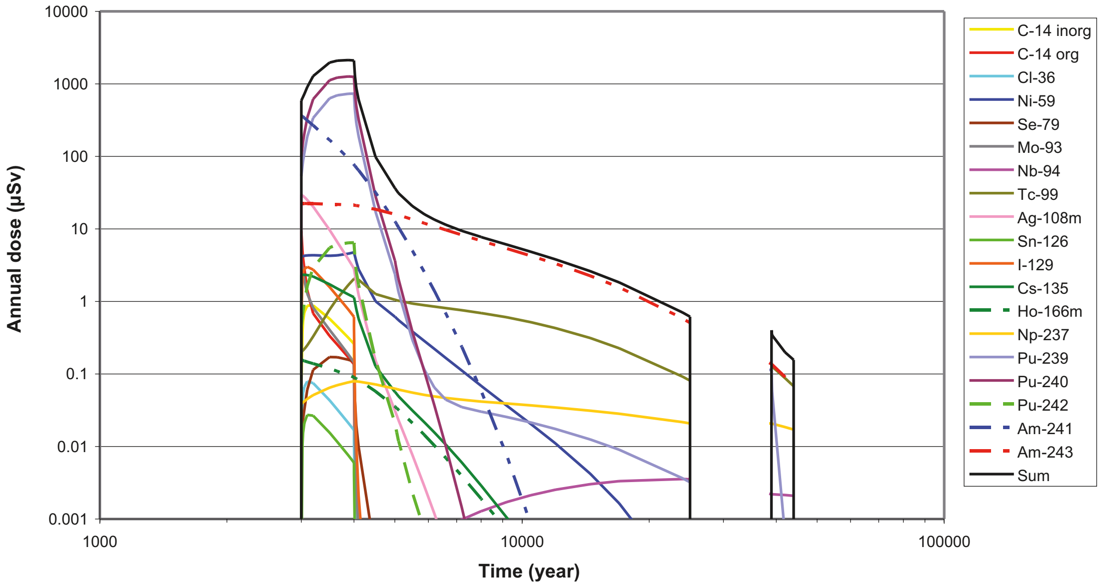


Figure 9-31. *Annual individual dose from the calculation case **"Intrusion well in repository" in combination with "High concentrations of complexing agents" for 1BTF**. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 ad to 39,000 ad) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

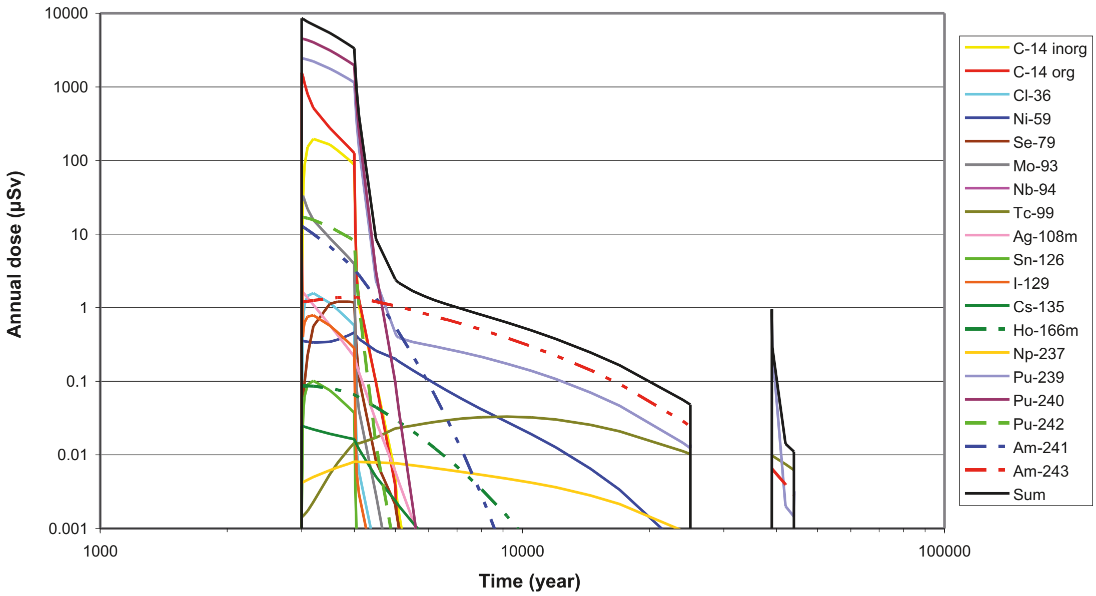


Figure 9-32. *Annual individual dose from the calculation case **"Intrusion well in repository" in combination with "High concentrations of complexing agents" for 2BTF**. No wells are assumed to exist under permafrost conditions (of which the first prevails from 25,000 ad to 39,000 ad) or during periods when the area above the repository is either ice-covered or submerged beneath the sea.*

9.5 Calculation cases for residual scenarios

In addition, doses have been calculated for releases of radionuclides in a number of residual scenarios. These scenarios are used, for example, to study the impact on transport and dose consequences when the influence of the barriers has been removed from the transport calculations.

9.5.1 Alternative inventory

Calculations have been carried out with an elevated inventory, up to the total quantity of activity for which the repository is licensed, see section 8.4.11. The activity of the individual radionuclides has thereby been scaled up by a factor of 7, causing the doses to increase by an equal amount, i.e. by a factor of 7, compared with the results for the main scenario's Weichselian variant, see Table 9-2.

9.5.2 No sorption in the near-field

Calculations of activity flows to the surface ecosystem were performed under the assumption that radionuclides did not interact at all with the near-fields of the repository parts, i.e. without sorption of the radionuclides in the near-fields of the repository parts. Other premises were the same as in the main scenario's Weichselian variant. This calculation case illustrates the scenario "Loss of barrier function, near-field I".

The dose curve for releases from all of SFR 1 is shown in Figure 9-33. The highest calculated dose increases by a factor of three compared with the main scenario's Weichselian variant, amounting to 35 μSv per year. It is caused by the release of inorganic C-14 from the silo and BMA. The inventories of inorganic C-14 are a factor of 2 higher than organic C-14 in the silo and BMA, see section 8.4. Since no sorption is taken into account in the near-field, inorganic C-14 therefore gives about twice the dose compared with organic C-14. The doses for releases from the silo increase considerably due to the higher inflow of radionuclides to the terrestrial ecosystem. Reduced sorption leads to considerably higher releases of both Ni-59 and Cs-135 than when sorption is taken into account, see Figure 9-4. It is these radionuclides that mainly cause the long-term doses. Subsequently, the silo's release of I-129 contributes to the doses. In contrast, I-129 from BMA has already been flushed out of BMA by this time.

9.5.3 Early degradation of engineered barriers

Dose results for the silo and BMA, for the calculation case where the barriers for the silo and BMA degrade so severely that they completely lose their retarding capability 3,000 years after closure, are shown in Figure 9-34. This calculation case illustrates the scenario "Loss of barrier function, near-field II".

Table 9-2. Highest calculated mean values of annual individual doses from the different repository parts and for all of SFR 1 for calculated releases from the repository with an alternative inventory. The dominant nuclides are also given. The highest individual dose occurs around 5,000 AD for all repository parts.

Repository part	Highest individual dose [μSv/year]	Dominant nuclide
Silo	32	organic C-14
BMA	37	organic C-14
1BTF	1.6	inorganic C-14
2BTF	17	inorganic C-14
BLA	0.1	inorganic C-14
Total SFR 1	82	organic C-14

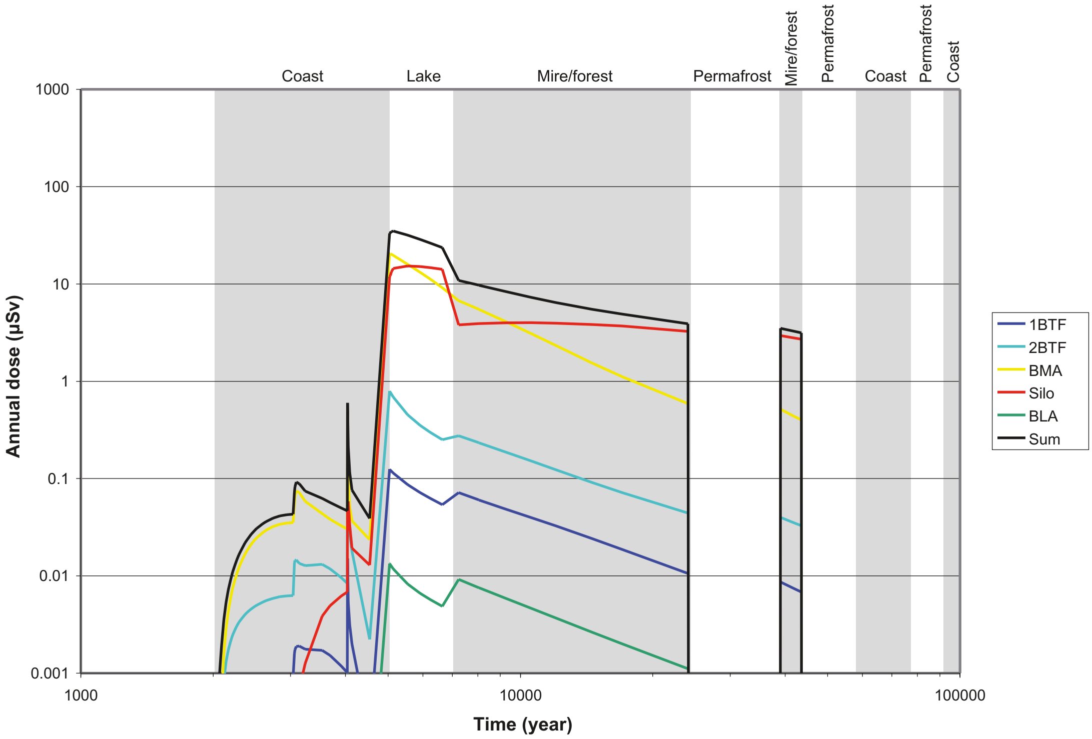


*Figure 9-33. Arithmetic mean values of annual individual doses for **all of SFR 1 and contributions of the different repository parts to these doses according to the calculation case "No sorption in the near-field"**. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

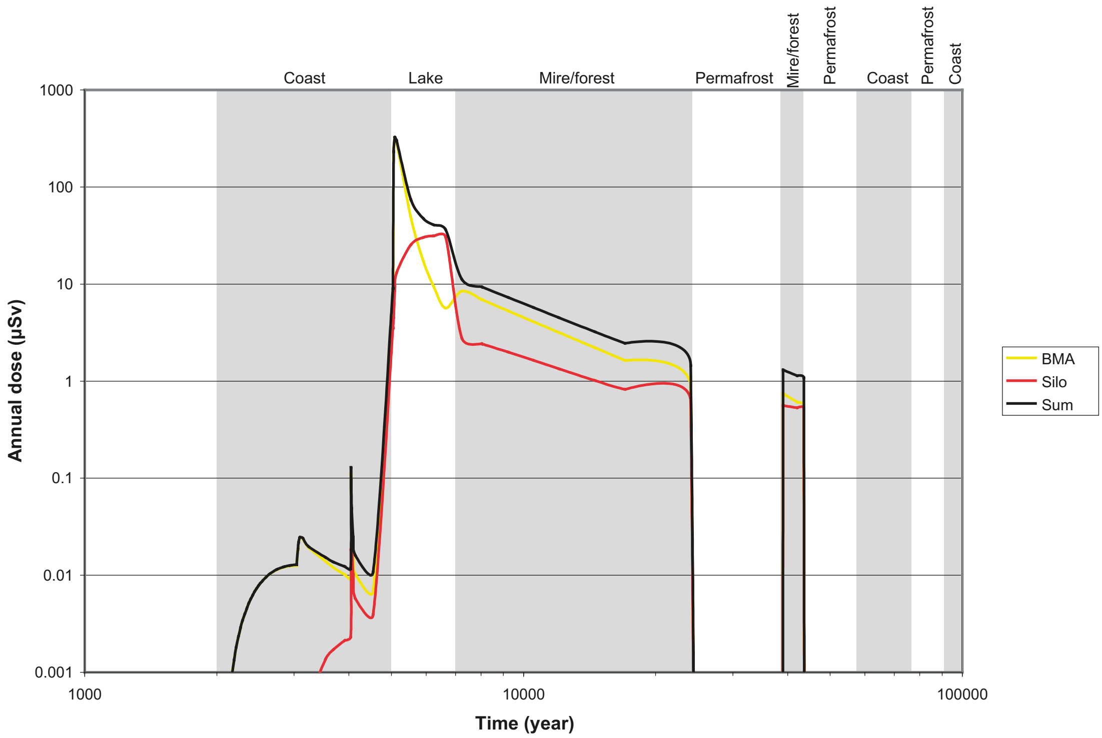


*Figure 9-34. Mean values of annual individual doses for calculated releases from **the silo and BMA according to the calculation case "Early degradation of engineered barriers"**. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see Figure 9-1.*

The calculations show a highest dose of 330 µSv per year, dominated by the release of inorganic C-14 from BMA, in a sudden pulse when the barriers have collapsed. In the case of the silo, which is surrounded by a low-permeable protective layer of bentonite mixture, the two chemical forms of C-14 cause a highest dose slightly later in time than the peak for BMA. In the long run, the repository parts make similar contributions to the total dose, but the dominant nuclides vary, see Figures 9-35 and 9-36. In the case of the silo, I-129 dominates the long-term doses, while the remaining bentonite layer retards Ni-59. This is not the case for BMA, where Ni-59 totally dominates the doses.

Figure 9-37 shows the dose curve for the main scenario's Weichselian variant and the dose curve for "Early degradation of engineered barriers". It is clearly evident from the figure that the sorbing and thereby retarding influence of the barriers on radionuclide transport is significant in minimizing the releases and thereby consequences to the environs. However, it is important from a safety viewpoint to see that even though the performance of the barriers is assumed to be greatly impaired only 3,000 years after closure, the doses are only one-third of the background radiation.

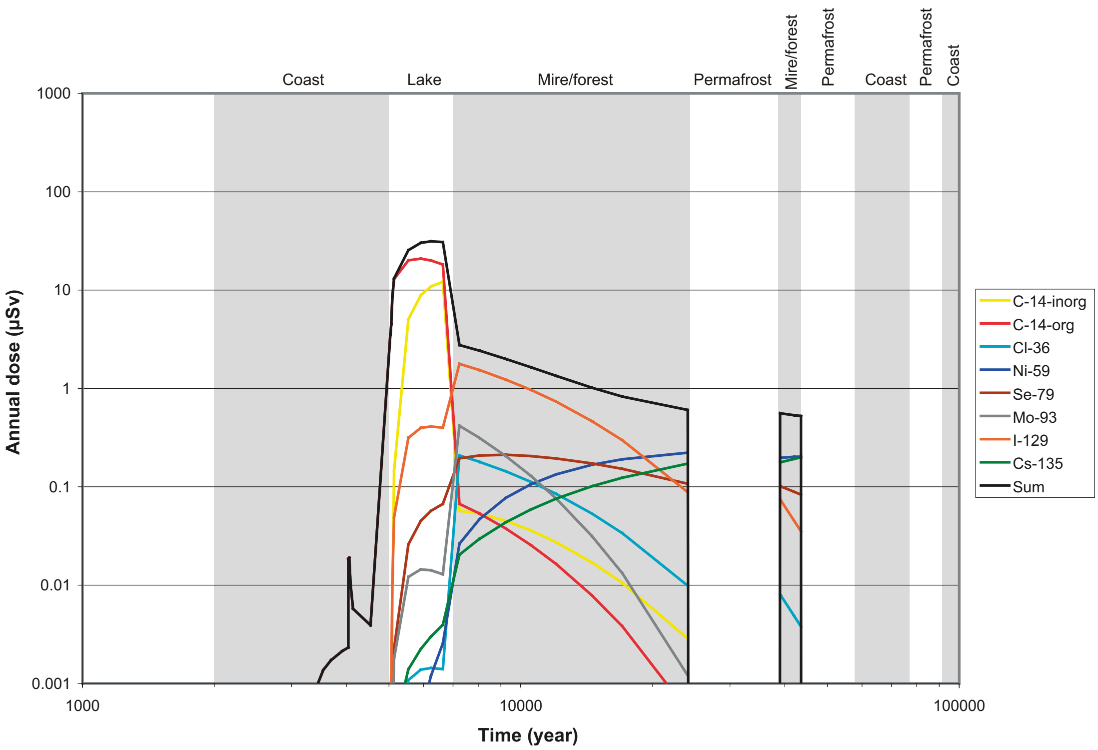


***Figure 9-35.** Arithmetic mean values of annual individual doses for calculated releases from **the silo according to the calculation case "Early degradation of engineered barriers"**. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see figure 9-1.*

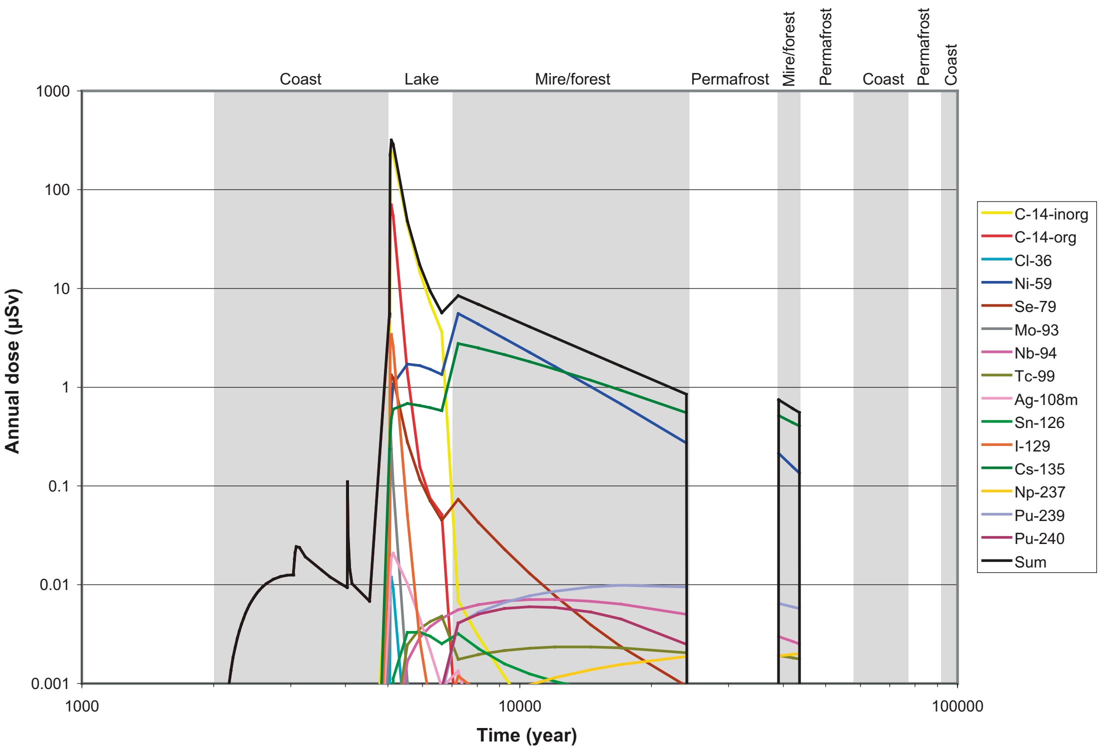


Figure 9-36. *Arithmetic mean values of annual individual doses for calculated releases from* ***BMA according to the calculation case "Early degradation of engineered barriers"****. Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see figure 9-1.*

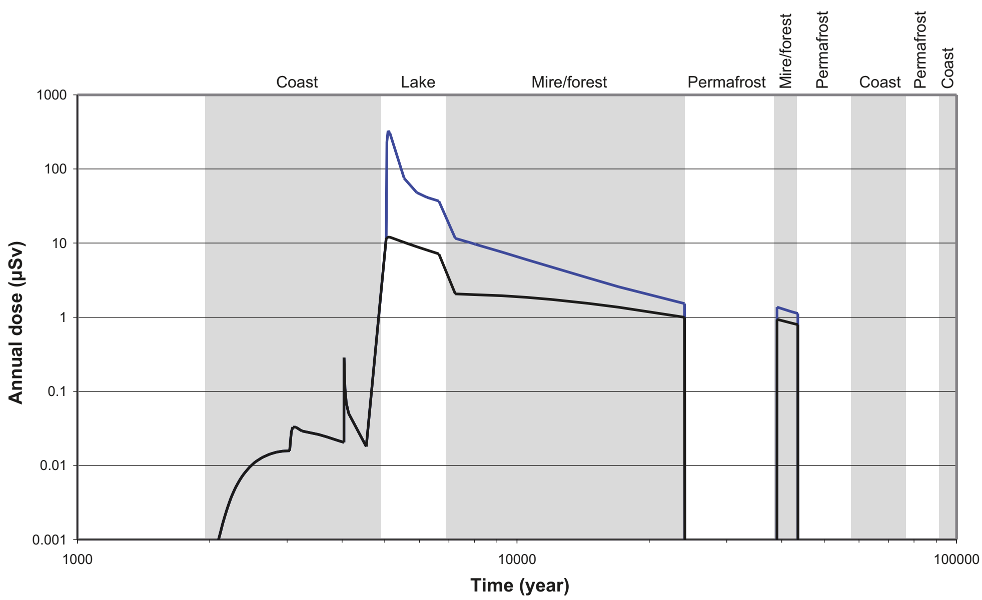


Figure 9-37. *Arithmetic mean values of annual individual doses for all of SFR 1 according to the calculation case "Early degradation of engineered barriers" (blue curve) and the dose curve for the main scenario's Weichselian variant (black curve). Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see figure 9-1.*

9.5.4 Loss of barrier function, far-field

In order to shed light on the function of the rock as a protective barrier, calculations were carried out where no retardation of radionuclides was taken into account during their transport through the geosphere. This calculation case illustrates the scenario "Loss of barrier function, far-field". The importance of the short-circuit, where calculated releases of radionuclides from the repository parts immediately reach the surface ecosystem, is shown in Figure 9-38, where the dose curve according to the main scenario's Weichselian variant is shown for comparison. The impact on the doses of neglecting transport and sorption of the radionuclides in the geosphere is marginal, as is evident from Figure 9-38. Retention in the rock does not affect the highest doses at all, due to the fact that organic C-14 is not sorbed in the rock. A slightly elevated level can be seen for inflow to the terrestrial surface ecosystem compared with the main scenario. The dose levels for the inflow to the terrestrial area are slightly higher than the dose levels calculated for the main scenarios.

9.5.5 Abandoned unclosed repository

The potential doses if the repository is abandoned without being closed is studied in the calculation case "Abandoned unclosed repository". It is assumed in the calculations that the water in the repository is used for drinking. Other premises for the calculations are described in section 8.4.16. The results are presented in Figure 9-39.

The results show that the highest dose, about 2,800 µSv, arises 200 years after the repository is abandoned. Ni-63 and Cs-137 are the nuclides that dominate the dose at this time. The dose then declines, and about 700 years after the repository has been abandoned, Ni-59 makes the biggest contribution to the dose.

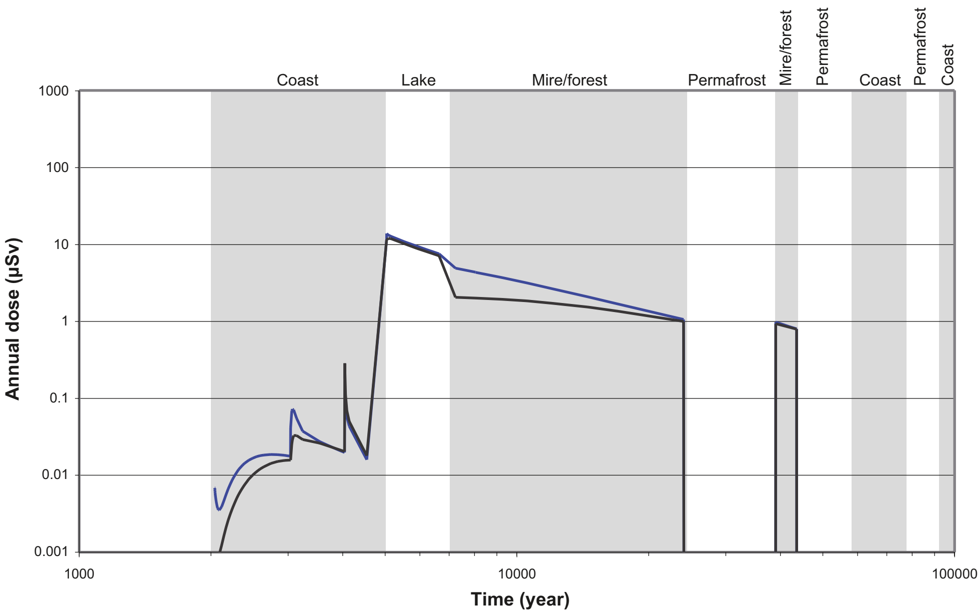


Figure 9-38. Arithmetic mean values of annual individual doses for all of ***SFR 1 according to the calculation case "Loss of barrier function, far-field"*** *(blue curve) and individual doses for the Weichselian variant (black curve). Periglacial conditions with continuous permafrost prevail from 25,000 AD to 39,000 AD, which is why there is no dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is beneath the sea, which is why the doses are lower than 0.001 µSv per year. For other explanations to the figure, see figure 9-1.*

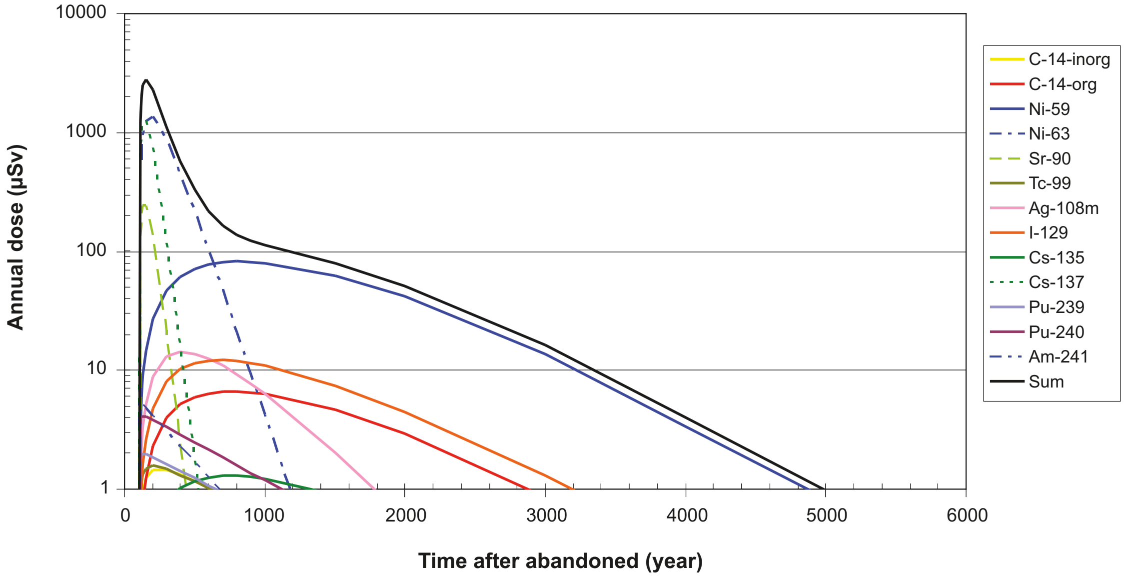


***Figure 9-39.** Annual individual dose for **all of SFR 1 according to the calculation case "Abandoned unclosed repository"**.*

9.6 Collective dose

According to SSI FS 1998:1, the collective dose shall also be calculated. It shall be calculated as the collective dose commitment integrated over 10,000 years from releases during the first 1,000 years after closure. The radionuclide C-14 dominates and gives a collective dose commitment of about 8 manSv from the main scenario's Weichselian variant /Bergström et al. 2008/. No appreciable difference in collective dose commitment is expected for the different calculation cases due to the fact that the releases during the first 1,000 years are dominated so strongly by organic C-14, which is not appreciably affected by other premises.

9.7 Discussion and conclusions

The results from the calculation cases show that it is only a few nuclides that cause the highest doses. They also show that the doses during the first 1,000 years after closure are low, due to low releases to a marine area with good water exchange and large water volumes. The releases are low during the first 1,000 years for all radionuclides except organic C-14. No radionuclides with half-lives shorter than 100 years make any significant dose contributions.

Dose calculations have been carried out for a main scenario with two climate variants, as well as for a number of less probable scenarios. Dose consequences have also been calculated for residual scenarios that are analyzed for the purpose of examining what it would mean for safety if certain barrier functions were completely lost.

Organic C-14 gives the highest flows of activity to the biosphere for most calculation cases /Thomson et al. 2008a/.

The highest annual mean individual doses from releases of radionuclides to the surface ecosystem for all calculation cases and all repository parts are summarized in Table 9-3. Table 9-4 summarizes the equivalent results for the calculation case "Well in discharge area". The doses for this case are based on the results of the release calculations for each of the other cases.

The highest calculated doses appear early, within a few thousand years after closure for the silo and rock vaults and thereby for all of SFR 1, with the exception of the doses from certain calculation cases for BMA. The exception is the calculation cases that examine the consequences of climate change towards a drier and colder climate and earlier freezing/bursting of BMA's barriers ("Early freezing in the Weichselian variant"). What characterizes all results is the fact that only a few radionuclides cause the highest doses. The first, and usually the highest, maximum occurs after 5,000 AD, and the dose is dominated by C-14. The radionuclides Cs-135, I-129 and Ni-59 dominate the late peaks after 7,000 AD if the inflow of radionuclides takes place to a terrestrial area.

In general, the two different climate variants considered in the main scenario do not result in great differences in the highest doses, due to the great importance for the dose of the early inflow of organic C-14 to the lake ecosystem. Some increase of the late doses can be seen in conjunction with the formation of a talik in the area, during permafrost periods occurring earlier than is assumed in the main scenario's Weichselian variant. This increase is due to releases of inorganic C-14 to a lake.

As expected, sorption of radionuclides in barriers affects the size of the dose. This is clearly evident from the calculation cases that illustrate the residual scenarios.

The doses for the main scenario combined with the calculation case "Well in discharge area" reach a maximum around 4,000 AD. The wells are all assumed to receive the releases that are calculated for the inflows of activity to the surface ecosystem. Releases of radionuclides from BMA give roughly equally large dose contributions for well and biosphere, while for silo inflow to the biosphere gives a higher dose. The opposite is true for the concrete tank repositories, BTF.

The "Intrusion well"cases give the highest doses in combination with the calculation cases that illustrate the main scenario and less probable scenarios. The highest calculated dose for all repositories and their calculation cases arises from a well that is drilled in the gravel fill surrounding 2BTF together with releases according to the premises of the case "High concentrations of complexing agents". However, it should be pointed out that very pessimistic assumptions have been used for these dose estimates.

If the repository is abandoned before closure, the dose is calculated to be 3,300 µSv per year and is caused mainly by Ni-63 and Cs-137. These radionuclides have a large inventory from the start, but due to their half-lives they decay rapidly. This dose corresponds to an average annual dose that we receive today if the dose from radon in our homes is included in addition to the natural background radiation of about 1,000 µSv per year.

Table 9-3. Highest calculated individual doses (μSv/year) for releases of radionuclides to the surface ecosystem for all calculation cases.

Scenario category	Scenario	Calculation case	Highest calculated individual dose (μSv/year), and in parentheses when it occurs if it does not occur between 5,000 and 6,000 AD					
			Silo	**BMA**	**1BTF**	**2BTF**	**BLA**	**SFR 1**
Main scenario	Weichselian variant	Weichselian variant	4.5	5.6	0.2	2.4	0.01	12
	Greenhouse variant	Greenhouse variant	4.5	5.6	0.2	2.4	0.01	12
Less probable scenarios	Early freezing of the repository	Early freezing in the Weichselian variant (BMA)						
		without talik	4.5	11 (39,000)	0.2	2.4	0.01	12
		with talik	4.5	6.9 (25,000)	0.2	2.4	0.01	12
		Extreme permafrost	4.5	13 (39,000)	0.2	2.4	0.01	13 (39,000)
		Extreme permafrost with talik	4.5	9.4 (22,000)	0.2	2.4	0.01	12
	Talik	Talik	4.5	5.6	0.2	2.4	0.01	12
	High concentrations of complexing agents	High concentrations of complexing agents	4.6 [a)]	6.1 [a)]	0.07 [a)]	0.3 [a)]	0.01 [a)]	11 [a)]
	Gas-driven advection	Gas-driven advection	4.5	5.6	0.2	2.4	0.01	12
	Wells	Well in discharge area	See Table 9-4					
		Intrusion well in repository						
		Weichselian variant	560 [b)]	73 [b)]	24 [b)]	1,600 [b)]	48 [b)]	
		High concentrations of complexing agents	820 [b)]	460 [b)]	2,100 [b)]	8,500 [b)]	48 [b)]	
Residual scenarios	Alternative inventory	Alternative inventory	32	37	1.6	17	0.1	82
	Loss of barrier function, near-field I	No sorption in the near-field	15	20	0.1	0.8	0.01	35 [c)]
	Loss of barrier function, near-field II	Early degradation of engineered barriers	31	320	0.2	2.4	0.01	330
	Loss of barrier function, far-field	Loss of barrier function, far-field	5.2	6.5	0.2	2.1	0.007	14
	Abandoned unclosed repository	Abandoned unclosed repository	–	–	–	–	–	2,800 (150 [d)])

[a)] Deterministically calculated, which is why the doses are slightly lower than the probabilistic results for the other cases, see Figure 9-3.
[b)] Maximum dose occurs immediately around 3,000 AD.
[c)] Maximum doses for the different repositories do not occur at the same time.
[d)] Time after abandonment of the repository.

Table 9-4. Highest calculated individual doses (µSv/year) for exposure from a well that is situated in the discharge area and is assumed to receive the nuclides that reach the surface ecosystem.

Scenario-category	Scenario	Calculation case	Highest calculated individual dose (µSv/year), and in parentheses when it occurs if not in 4,000 AD					
			Silo	BMA	1BTF	2BTF	BLA	All rock vaults
Main scenario	Weichselian variant	Weichselian variant	0.9	5.7	1.4	8.0	0.5	16
	Greenhouse variant	Greenhouse variant	0.9	5.7	1.4	8.0	0.5	16
Less probable scenarios	Early freezing of the repository	Early freezing in the Weichselian variant (BMA)						
		without talik	0.9	17 (39,000)	1.4	8.0	0.5	17 (39,000)
		with talik	0.9	5.7	1.4	8.0	0.5	16
		Extreme permafrost	2.0	21 (39,000)	1.4	8.0	0.5	21 (39,000)
		Extreme permafrost with talik	0.9	5.7	1.4	8.0	0.5	16
	Talik	Talik	0.9	5.7	1.4	8.0	0.5	16
	High concentrations of complexing agents	High concentrations of complexing agents	2.7	10	2.2	6.4	0.5	19
	Gas-driven advection	Gas-driven advection	0.9	5.7	1.4	8.0	0.5	16
Residual scenarios	Alternative inventory	Alternative inventory	5.9	27	9.9	56	3.6	97
	Loss of barrier function, near-field I	No sorption in the near-field	16	89	4.1	11	0.8	110
	Loss of barrier function, near-field II	Early degradation of engineered barriers	12	120	1.4	8.0	0.5	130

10 Assessment of risk

10.1 Introduction

This chapter begins with a presentation of the regulatory requirements on limitation of risk, how risk should be calculated and what levels are limiting. This is followed by a presentation of the method that has been used to estimate risk based on the dose results and probabilities reported in Chapter 9 and Chapter 7. Possible combinations of scenarios (identified in Chapter 8, section 8.5), serve as a basis for the calculation of the aggregate risk that is presented for each scenario. Finally, an account is given of how uncertainties in the safety assessment are handled in the light of the results of the risk calculations.

10.1.1 Regulatory requirements

Both man and the environment must be protected from harmful effects from the repository. The regulatory authorities, in this case the Swedish Radiation Protection Authority (SSI), issue regulations (and associated guidelines), which the licensee of a nuclear facility must demonstrate that the facility complies with.

The following regulations for protection of human health apply to the long-term safety of SFR 1:

SSI's regulations FS 1998:1 and associated guidelines FS 2005:5 provide that:

"A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk." (SSI FS 1998:1)

Risk is defined as *"the product of the probability of receiving a radiation dose and the harmful effects of the radiation dose."* (SSI FS 1998:1)

Harmful effects are defined as *"cancer (fatal and non-fatal) as well as hereditary effects in humans caused by ionizing radiation, in accordance with paragraphs 47-51 in Publication 60, 1990, of the International Commission on Radiological Protection."* (SSI FS 1998:1)

"According to the regulations, the recommendations of the International Commission on Radiological Protection (ICRP) are to be used for calculation of the harmful effects of ionizing radiation. According to ICRP publication no. 60, 1990, the factor for conversion of effective dose to risk is 7.3 percent per sievert." (SSI FS 2005:5)

"One way of defining the most exposed group is to include the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk. If a larger number of individuals can be considered to be included in such a group, the arithmetic average of individual risks in the group can be used for demonstrating compliance with the criterion for individual risk in the regulations. One example of an such exposure situation is a release of radioactive substances into a large lake that can be used as a source of drinking water and for fishing." (SSI FS 2005:5)

"If the exposed group only consists of a few individuals, the regulatory criterion for individual risk can be considered to be complied with if the highest calculated individual risk does not exceed 10^{-5} per year. An example of a situation of this kind might be if consumption of drinking water from a drilled well is the dominant exposure path. In such a calculation example, the choice of individuals with the highest risk load should be justified by information about the spread in calculated individual risks with respect to assumed living habits and places of sojourn." (SSI FS 2005:5)

"Individual risk should be calculated as an annual average on the basis of an estimate of the lifetime risk for all relevant exposure pathways for each individual. Lifetime risk can be calculated as the accumulated lifetime dose multiplied by the conversion factor of 7.3 per cent per sievert." (SSI FS 2005:5)

A probabilistic analysis can in certain cases *"provide an inadequate picture of how a single event that damages the final repository, such as a major earthquake, affects the risk for a single generation."* In these cases the probabilistic calculations should be "*supplemented by calculating the risk for the individuals who are assumed to live after the event has taken place and who are affected by its calculated maximum consequence. The calculations can be done for instance by illustrating the importance of the event occurring at different times (T1, T2 …,Tn), taking into consideration the probability of the event occurring during the respective time interval...*". (SSI FS 2005:5)

Risk criteria are lacking for protection of the environment. Here SSI FS 1998:1 says: *"The final management of spent nuclear fuel and nuclear waste shall be implemented so that biodiversity and the sustainable use of biological resources are protected against the harmful effects of ionizing radiation"*.

Based on a conversion factor of 7.3 percent per sievert /SSI 2005:5/, annual risks of 10^{-5} and 10^{-6} correspond to a dose of 140 and 14 μSv per year, respectively. These doses correspond to approximately 10% and 1%, respectively, of the natural background radiation in Sweden.

10.1.2 Method for risk estimation

In order to determine whether the repository complies with the above risk criteria, annual doses to a representative individual in the group exposed to the highest risk have been calculated for a number of scenarios (Chapter 9). The arithmetic mean value of the annual dose for a calculation case obtained from probabilistic calculations has been used together with probability assessments for the scenarios (Chapter 7) and the conversion factor 7.3 percent per sievert (stipulated in SSI FS 2005:5) to obtain annual risks. The method for estimation of risk for the scenario "Earthquake" is described in sections 7.6.1 and 8.4.3. For each scenario, an estimate is made of the risk for the cases without well and with well in the discharge area, and for some scenarios also for intrusion well in the repository. The aggregate risk for a scenario therefore consists of the sum of the risks for the cases without well and with the well that gives the highest risk. The estimated risks are compared with the regulatory authorities' risk criteria.

In the biosphere calculations without well, the fact that the ecosystem changes with time is taken into consideration. During periods when the ecosystem consists of a future lake, exposure from consumption of drinking water from the lake is taken into consideration. This means that exposure via consumption of water is included in the risk estimate both with and without well, so that addition of the risks leads to an overestimate. However, consumption of fish dominates the exposure from the lake, so the overestimate is only of marginal importance /Bergström et al. 2008/. This applies to all scenarios where a combination with and without well occurs.

It is pessimistically assumed in the dose calculations that the entire radionuclide flow takes place to a limited area in the biosphere from which further transport takes place. The principle for the risk calculations has been to study the risk resulting from the fact that an individual in the exposed group takes all his food from the ecosystem that gives the highest dose.

In cases where a scenario is described by more than one calculation case, the risk for the scenario is represented by the calculation case that gives the highest risk.

There is no risk criterion for protection of the environment like there is for humans. The repository's impact on the environment is shown by calculating the highest concentrations of the radionuclides in the environs. The environmental impact is assessed by calculating the Risk Quotient (RQ) between the calculated concentrations and EMCLs (Environmental Media Concentration Limits), as proposed in the EU project ERICA /ERICA 2008, Beresford et al.

2007/. If the RQ is less than one, this shows according to the ERICA project that no further analysis is required to show effects on the environment. The method used in ERICA to obtain EMCLs is described in the FASSET project /FASSET 2004, Larsson 2004/.

10.1.3 Applicable risk criterion

The number of individuals in the most exposed group is of importance for determining what risk should be used for assessment of repository safety. If the exposed group only consists of a few individuals, the criterion of the regulations for individual risk can be considered to be complied with if the highest calculated individual risk does not exceed 10^{-5} per year (SSI FS 2005:5). SSI says that a well is an example of this. In this assessment a well is not the only case that is judged to expose a limited number of individuals. There is a discussion in section 10.5 regarding an applicable risk criterion over time.

In addition to the requirement that the exposed group shall consist of a few persons in order for the results of the safety assessment to be evaluated against the risk criterion of 10^{-5} per year, there is an additional prerequisite. The risk for the individual who receives the highest risk load must be taken into account.

10.2 The main scenario

The dose for the main scenario has been analyzed with two variants of climate change, neither of which is considered more probable than the other in the present safety assessment, see Chapter 7, section 7.4. The first, the Weichselian variant, is based on a repetition of reconstructed conditions for the last glacial cycle. The second, the greenhouse variant, describes a climate with an anthropogenically increased greenhouse effect. The calculated highest dose is the same for both variants, see Figures 9-1 and 9-14. This is because the highest dose occurs relatively early in the evolution of the repository, while the two variants of the main scenario are still the same. The risk has been calculated for both variants, but in this section, 10.2, only the risk for the Weichselian variant is described. The results for the greenhouse variant are also presented in the summary of the risks in section 10.5.

The possibility cannot be excluded that a well is drilled in the repository's discharge area, or that an intrusion well is drilled down into the repository. The dose for the main scenario has been calculated for a succession of ecosystems and the two alternative well locations in the scenario "Wells". The risk for the main scenario therefore comprises the sum of the risk for the main scenario without well and the risk obtained from a well in the repository's discharge area or an intrusion well in the repository. Between 5,000 AD and 7,000 AD, when a lake comprises the recipient, exposure is counted via consumption of water in both the cases, with and without well. During this period, this exposure pathway is thus counted twice. However, this is negligible since the risk for the lake is dominated by fish from the lake /Bergström et al. 2008/.

In summary, the following steps have been carried out to calculate the aggregate risk for the main scenario:

- The dose for the main scenario has been calculated, see sections 9.2 and 9.3.
- The probability for the main scenario is high and has been set at 1, see Table 7-18.
- The probability that there will be a well in the repository's discharge area during a person's lifetime has been set at 0.1, see section 7.6.7 or Table 7-18.
- The probability of an intrusion well is estimated in section 7.6.7 (see also Table 7-18) to be about $4 \cdot 10^{-4}$ for the silo and about $1.5 \cdot 10^{-3}$ for the rock vaults.
- The risk for the main scenario without well is calculated, see section 10.2.1.
- The risk for a well in the repository's discharge area is calculated, see section 10.2.2.

- The risk for an intrusion well in the repository is calculated, see section 10.2.3.
- The calculated risk for the the well that gives the highest risk is added to the risk for the main scenario without well, see section 10.2.4.

10.2.1 Risk for main scenario without well

The main scenario is illustrated with two calculation cases that give the same highest risk for release from the repository. The risk for the calculation case "Weichselian variant" is shown in Figure 10-1. In order to visualize the spread in the calculated risk that is obtained in the probabilistic calculations, the median is also shown in Figure 10-1 together with the 5th and 95th percentiles for the risk. It can be seen in the figure that the risk distribution is skewed and the mean value lies above the median value. The mean value has been used in all risk calculations.

The highest risk, approximately $9 \cdot 10^{-7}$ per year, occurs just after 5,000 AD in a lake ecosystem and is mainly caused by organic C-14 from the silo and BMA and by inorganic C-14 from 2BTF.

10.2.2 Risk for well in discharge area

In the calculations of doses for well in the discharge area, it is assumed that the well is situated so that the entire radionuclide release from all rock vaults or the silo reaches the well. The well cannot be situated so that it receives releases from the rock vaults and the silo simultaneously, see section 6.5.2.

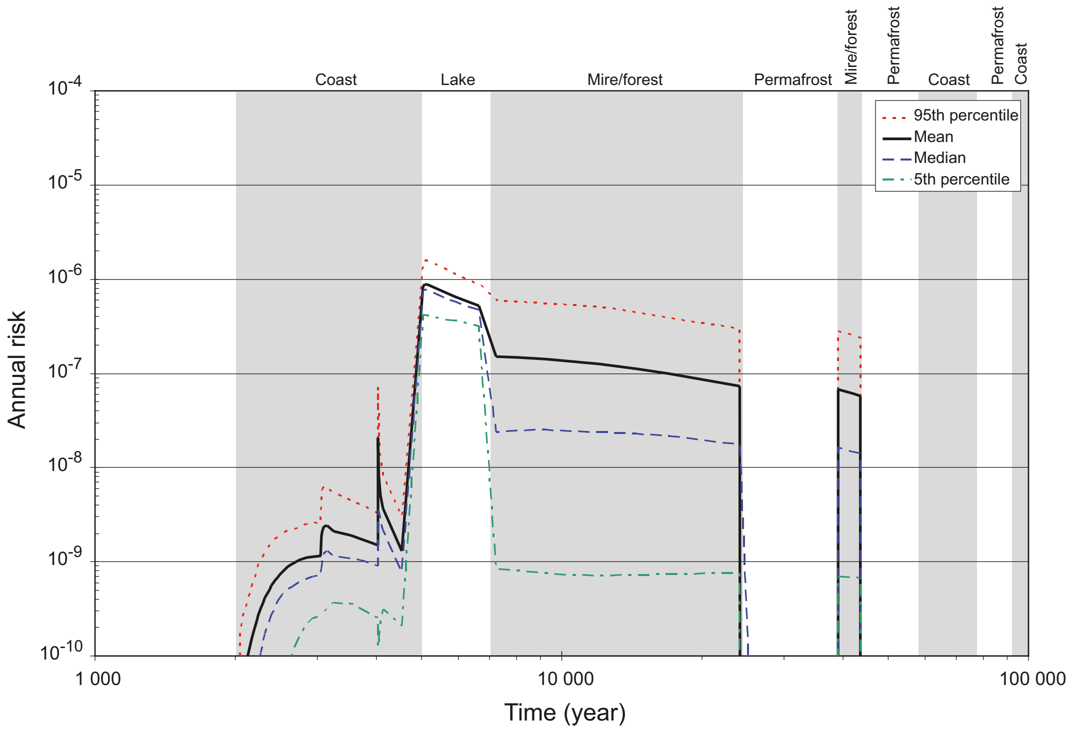


Figure 10-1. Mean, median and 5th and 95th percentiles for the probabilistically calculated risk for the main scenario's Weichselian variant, without well. Periglacial conditions with continuous permafrost prevail between 25,000 AD and 39,000 AD, which explains the low dose during this period. After 44,000 AD there is continuous permafrost, an ice sheet or a situation where the repository area is submerged.

The following highest doses have been calculated, see Chapter 9:

- The highest dose from the silo is 0.9 μSv/year.
- The highest dose from the rock vaults is approximately 16 μSv/year, with the highest contribution from 2BTF (8 μSv/year) and BMA (6 μSv/year).

The highest dose for the well case comes from the rock vaults, which, together with a probability of 0.1, gives a risk of $1 \cdot 10^{-7}$ per year. This risk occurs at about 4,000 AD, in conjunction with a peak in the outflow of activity from the geosphere caused by incremental changes in the hydrogeological parameters in the transport model. This gives an overestimate in dose and risk, see section 8.2.6.

Figure 10-3 shows the risk for a well situated in the discharge area from the rock vaults. The risk is shown up to 44,000 AD. After that time there is continuous permafrost, an ice sheet or a situation where the repository area is submerged, which means no wells can be drilled, see Figure 8-16.

The fact that a well is drilled in the repository's discharge area can be regarded as an individual event which, if it occurs, can make a considerable risk contribution. The probability that a well exists in the repository's discharge area at any given moment is limited. The cumulative probability that a well exists in the repository's discharge area at some time up to a given point in time can, however, be considerable during the studied period. Risk dilution for a well in the discharge area therefore needs to be discussed, see section 10.4.2.

10.2.3 Risk for intrusion well

In the calculations of doses for an intrusion well it is assumed that it has been drilled directly down into one of the rock vaults or the silo. The direct consequence for the individual who makes the intrusion is not assessed; rather, the dose has been calculated assuming that the water in the gravel fill in the particular repository part is consumed. An intrusion well cannot be drilled in the repository before 3,000 AD or after 44,000 AD. This is due to the fact that the repository area is initially submerged beneath the sea, and there is no temperate period after 44,000 AD when wells could be drilled down into the repository, see Figure 8-16.

The highest doses caused by a drinking water well in the repository occur around 3,000 AD and amount to 560 μSv/year for the silo, 73 μSv/year for BMA, 24 μSv/year for 1BTF, 1,600 μSv/year for 2BTF and 48 μSv/year for BLA, see section 9.4.9.

The probability for an intrusion well is estimated in section 7.6.7 (see also Table 7-18) to be about $4 \cdot 10^{-4}$ for the silo and about $1.5 \cdot 10^{-3}$ for the rock vaults.

The risk as a function of time for an intrusion well drilled in each particular repository part is shown in Figure 10-2. The highest risk from the different repository parts is shown in Table 10-1. The highest risk is dominated by an intrusion well in 2BTF. The hydrogeological calculations (see /Holmén and Stigsson 2001a/), show that if a well is drilled in any of the rock vaults, the well will attract a large portion of the flow from the other rock vaults as well, see section 6.5.2. If a well has been drilled in, for example, 2BTF, the water in 2BTF would thus be diluted by the water from the other rock vaults, which contain a lower concentration of radionuclides. Dilution of the water has not been taken into account; instead, the highest risk for the calculation case "Intrusion well in rock vaults or silo" has been set at $2 \cdot 10^{-7}$ per year at 3,000 AD.

Risk dilution for intrusion wells is also discussed in section 10.4.

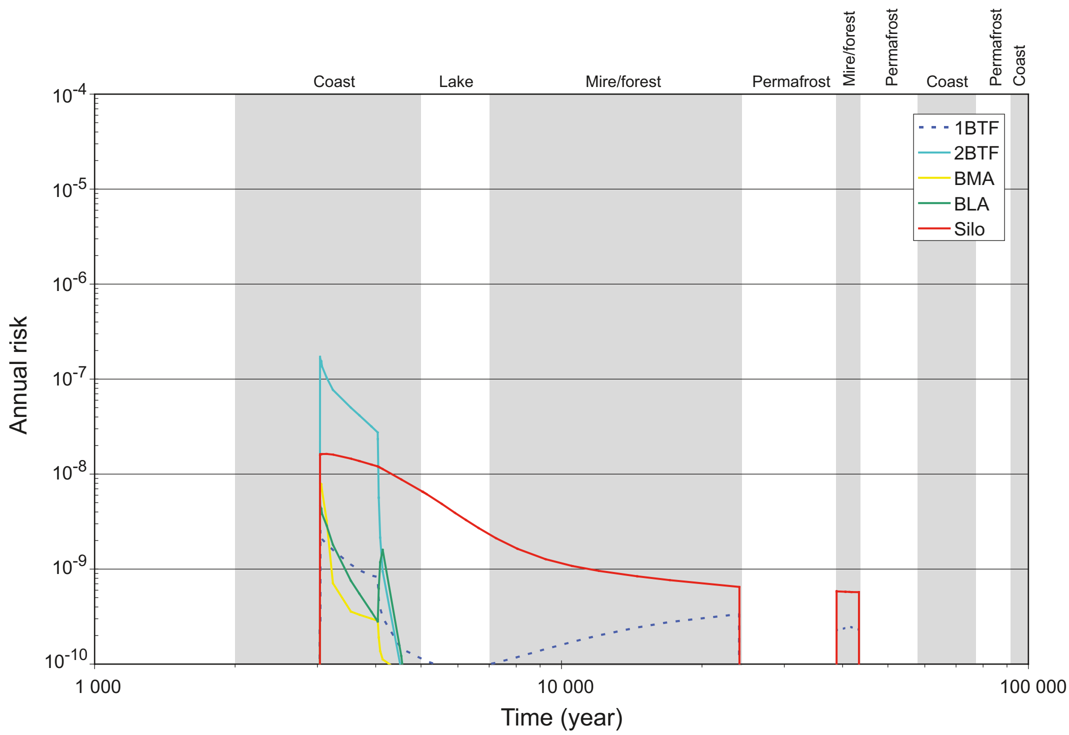


Figure 10-2. Calculated risk for an intrusion well drilled in the different repository parts in the Weichselian variant. It is not judged possible for a drinking water well to be drilled in the repository until 3,000 AD, since the repository area is covered by the sea before that time. After 44,000 AD there will be no more temperate periods when wells could be drilled down into the repository.

Table 10-1. Highest risk from a particular repository part for an intrusion well in the Weichselian variant.

Repository part	Silo	BMA	1BTF	2BTF	BLA
Risk	$2 \cdot 10^{-8}$	$8 \cdot 10^{-9}$	$3 \cdot 10^{-9}$	$2 \cdot 10^{-7}$	$5 \cdot 10^{-9}$

10.2.4 Aggregate risk for main scenario

The aggregate risk for the main scenario has been calculated by adding the risk for the main scenario's Weichselian variant without well to the risk for the well that gives the highest risk at any given time. The risks for the Weichselian variant without well, for a well in the discharge area and for an intrusion well are shown in Figure 10-3 together with the aggregate risk for the Weichselian variant. It has been assumed in calculating the risk for the intrusion well in Figure 10-3 that it is situated in the repository part which gives the highest risk at any given time according to Figure 10-2.

The highest aggregate risk for the main scenario is $9 \cdot 10^{-7}$ per year at 5,000 AD and is dominated by the risk for the main scenario without well.

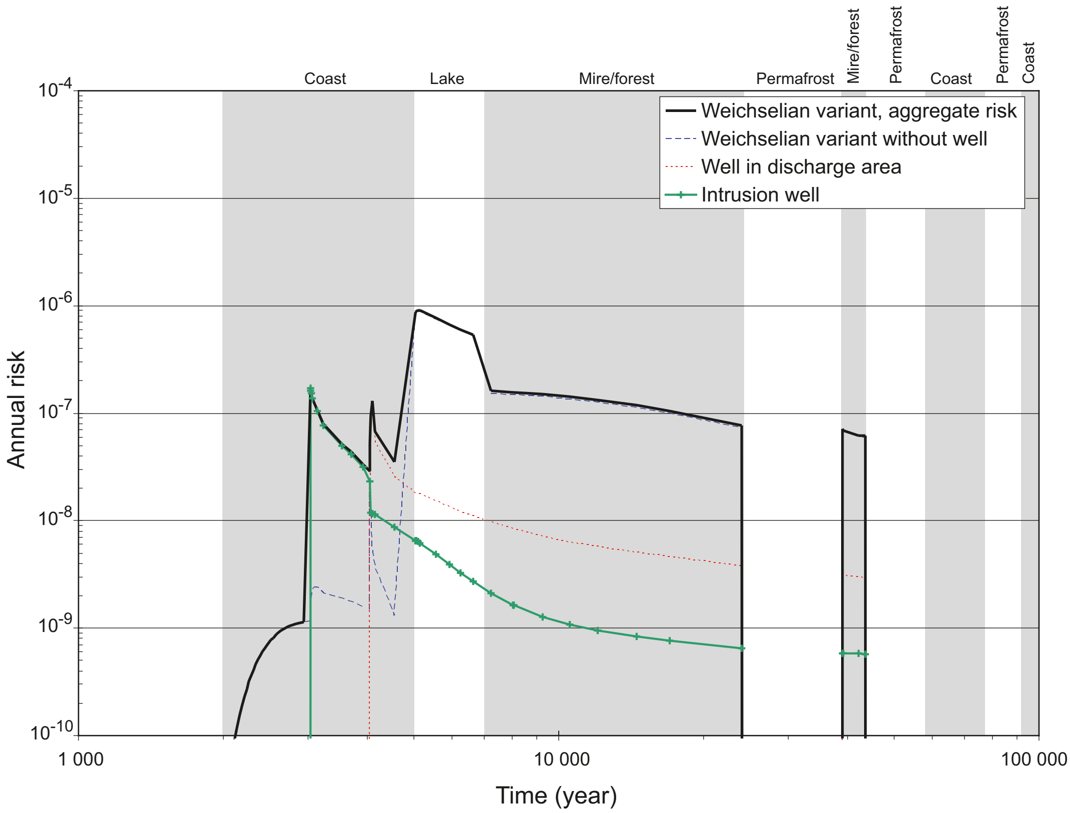


Figure 10-3. *Calculated risks for the main scenario's Weichselian variant without well, for a well in the discharge area and for an intrusion well, as well as the aggregate risk for the Weichselian variant. Before 3,000 AD and after 44,000 AD, conditions on the site are judged to be such that a drinking water well cannot be drilled into the repository. Periglacial conditions with continuous permafrost prevail between 25,000 AD and 39,000 AD, which explains the low dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is submerged.*

10.2.5 Effects on the environment

The repository's impact on the environment has been shown by calculating the highest concentrations of radionuclides in fresh water, brackish water and soil /Bergström et al. 2008/. A Risk Quotient ("RQ") has then been calculated by dividing these concentrations by the proposed EMCLs /ERICA 2008/. If the RQ is less than one, the impact on the environment is judged to be negligible according to the ERICA project. EMCLs for brackish water are lacking, so instead values for marine water have been used to calculate the RQs for brackish water. EMCLs for marine water are generally lower than for fresh water (except for Cl-36 and the caesium isotopes), which means that the calculated RQs for brackish water are deemed to be overestimated.

Tables 10-2 and 10-3 show calculated RQs for the radionuclides that give the highest RQs. It is evident from the tables that all RQs are less than one, which means that no further studies are needed of environment impact according to the methodology described in section 10.1.2. The nuclides that exhibit the highest RQs are C-14 and Ni-59 in fresh water.

Table 10-2. Compilation of calculated concentrations, EMCLs[1)]/ERICA 2008/ and RQs for radionuclides in fresh water and brackish water.

Radionuclide	Concentration [Bq/m^3]	EMCL[1)] [Bq/m^3]	RQ
Fresh water			
C-14 org	$4.0\cdot10^{2}$	$1.6\cdot10^{4}$	$3\cdot10^{-2}$
C-14 inorg	$1.9\cdot10^{2}$	$1.6\cdot10^{4}$	$1\cdot10^{-2}$
Ni-59	$4.0\cdot10^{2}$	$5.7\cdot10^{4}$	$7\cdot10^{-3}$
Brackish water[2)]			
Co-60	$5.1\cdot10^{-4}$	7.9	$6\cdot10^{-5}$
C-14 org	$1.2\cdot10^{-1}$	$6.5\cdot10^{3}$	$2\cdot10^{-5}$
C-14 inorg	$5.8\cdot10^{-2}$	$6.5\cdot10^{3}$	$9\cdot10^{-6}$

[1)] Environmental Media Concentration Limit.

[2)] EMCL for marine water /ERICA 2008/.

Table 10-3. Compilation of calculated concentrations, EMCLs[1)]/ERICA 2008/ and RQs for radionuclides in soil.

Radionuclide	Concentration [Bq/kg dry weight]	EMCL[1)] [Bq/kg dry weight]	RQ
Soil			
I-129	$6.5\cdot10^{-1}$	$4.3\cdot10^{2}$	$2\cdot10^{-3}$
Ni-59	$1.8\cdot10^{3}$	$1.4\cdot10^{6}$	$1\cdot10^{-3}$
C-14 org [2)]	$2.4\cdot10^{-2}$	$8.3\cdot10^{1}$	$3\cdot10^{-4}$

[1)] Environmental Media Concentration Limit.

[2)] Concentration in the ground-level air layer [Bq/m^3 air], EMCL [Bq/m^3 air].

10.3 Less probable scenarios

A number of less probable scenarios have been analyzed to cover uncertainties in the evolution of the repository and its environs. Dose results are presented in section 9.4.

10.3.1 Earthquake

In this scenario it is assumed that an earthquake destroys the engineered barriers in the silo and BMA. Probability distributions for the probability that an earthquake of a given magnitude will occur in the Forsmark area are shown in section 7.6.1. Results for the scenario in the form of annual calculated risk are presented below. A brief description of the calculations is given in sections 8.4.3 and 7.6.1. A more detailed description of methodology and results is given in /Bergström et al. 2008/.

Risk is shown for the silo and BMA in Figures 10-4 and 10-5, respectively. The risk is shown for earthquakes of different magnitudes, from 3 to 6. The calculation case is set up so that the calculated dose from an earthquake that destroys the barriers is the same, regardless of the magnitude of the earthquake. Earthquakes of lower magnitude have a higher probability of occurring, so the highest risk is obtained for the lowest-magnitude earthquake.

It can be seen from Figures 10-4 and 10-5 that the risk of a magnitude 3 earthquake decreases rapidly during the first period with release to a mire. This is because there is a great probability that a magnitude 3 earthquake will already have occurred. The radiological risk is calculated as a function of the recurrence time for an earthquake, where the risk declines for each period during which an earthquake should statistically already have occurred. Table 7-10 indicates that the recurrence time for a magnitude 3 earthquake is approximately 2,700 years.

No analysis of the repository's ability to withstand earthquakes has been carried out in SFR 1 SAR-08, but the repository is estimated to remain intact when subjected to earthquakes of less than magnitude 5, see section 7.6.1.

Figure 10-6 summarizes the total risk for the scenario for a magnitude 5 earthquake. In order to obtain the total risk from the repository, the risk from the BTF repositories and BLA for the main scenario's Weichselian variant without well has been added to the earthquake risk from the silo and BMA. The highest annual risk for the scenario amounts to $8 \cdot 10^{-7}$ per year at 5,000 AD.

Risk dilution for the scenario "Earthquake" is discussed in section 10.4.

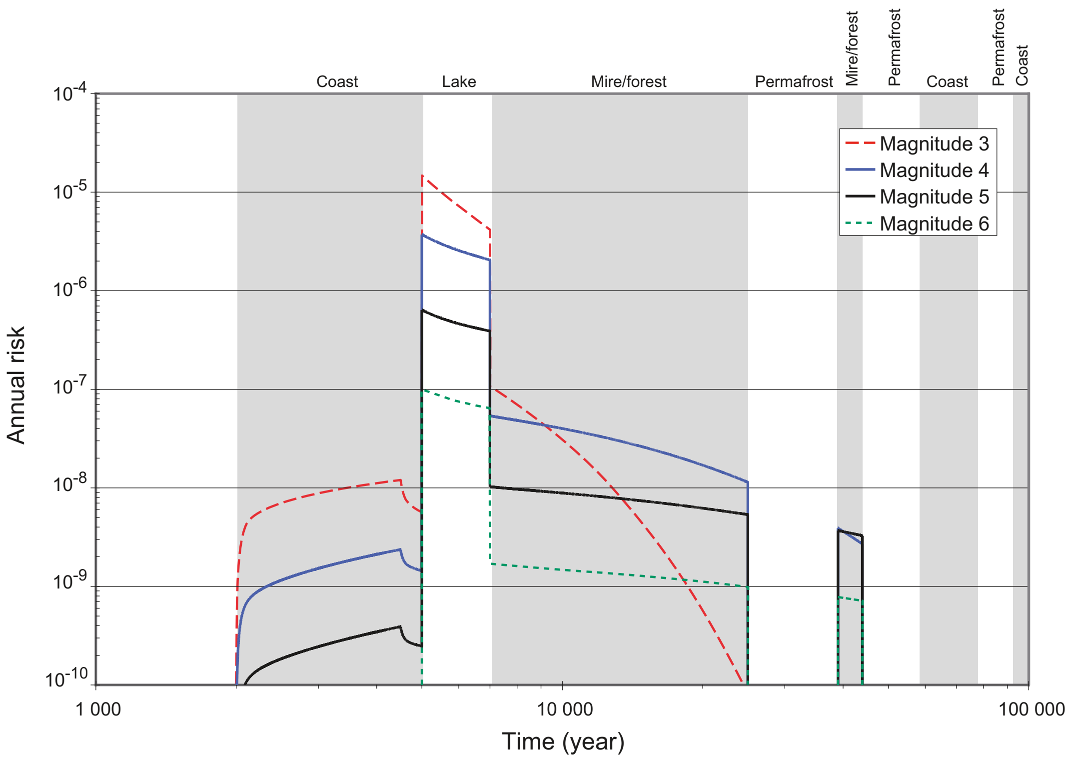


__Figure 10-4.__ Annual risk for the silo repository caused by earthquakes of different magnitudes. The dose for an earthquake has been posited to be the same, regardless of magnitude. Earthquakes of lower magnitude have a higher probability of occurring, which means that the earthquake with the lowest magnitude has the highest risk.

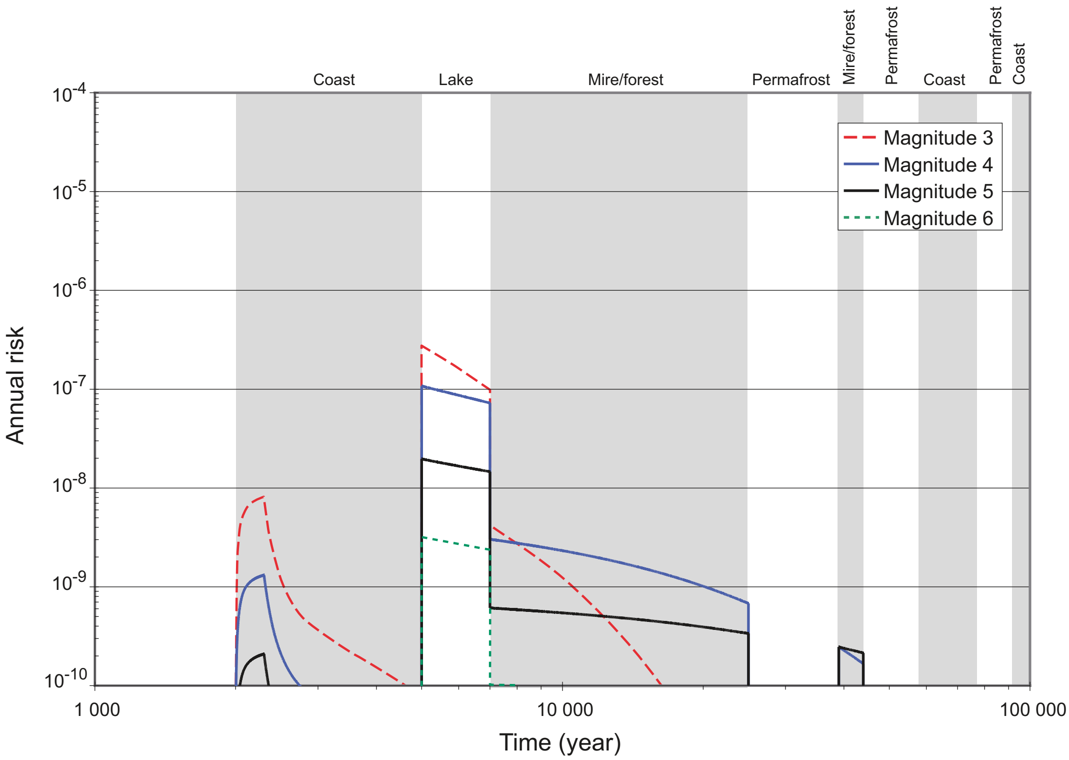


Figure 10-5. *Annual risk for BMA caused by earthquakes of different magnitudes. The dose for an earthquake has been posited to be the same, regardless of magnitude. Earthquakes of lower magnitude have a higher probability of occurring, which means that the earthquake with the lowest magnitude has the highest risk.*

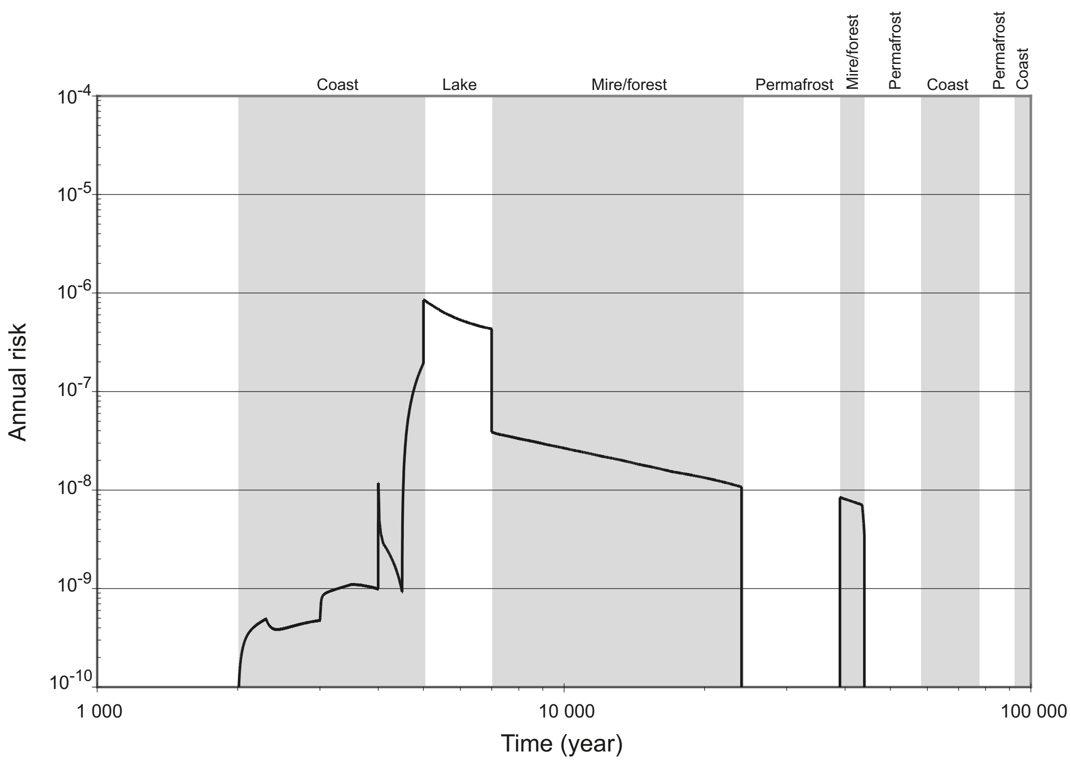


Figure 10-6. *Calculated risk for the scenario "Earthquake" for a magnitude 5 earthquake for all of SFR 1. The risk has been calculated by adding the risk for the "Earthquake" scenario for the silo and BMA to the risk for the Weichselian variant without well for the BTF repositories and BLA. Periglacial conditions with continuous permafrost prevail between 25,000 AD and 39,000 AD, which explains the low dose during this period. After 44,000 years there is continuous permafrost, an ice sheet or a situation where the repository area is submerged.*

10.3.2 Early freezing of the repository

The scenario "Early freezing of the repository" is represented by four calculation cases, none of which is judged to be more probable than the others. Of these, the calculation case "Extreme permafrost" gives rise to the highest dose, see Table 8-3 and Table 9-3. Other calculation cases gives highest doses that do not exceed the dose for the main scenario.

The calculation case "Extreme permafrost" is based on an alternative climate evolution that favours the formation of permafrost, see section 8.4.6. In section 7.6.2, the probability of the climate evolution that generates this calculation case is judged to be less probable than the main scenario's two climate variants. But it is deemed to be impossible to assign a numerical value to the probability of the scenario. A probability of one has therefore been pessimistically used in the calculations. Risk as a function of time for the calculation case "Extreme permafrost" is shown in Figure 10-7.

The scenario's highest risk without well amounts to $1 \cdot 10^{-6}$ per year at 39,000 AD.

Risk as a function of time for the calculation case "Extreme permafrost with well in the discharge area" is also shown in Figure 10-7. The highest risk for well in the discharge area in this scenario amounts to $2 \cdot 10^{-7}$ per year and occurs in 39,000 AD.

The highest aggregate risk for the scenario "Early freezing of the repository" has been calculated to be $1 \cdot 10^{-6}$ per year and occurs in 39,000 AD. The highest risk coincides with a peak value of release from the geosphere during a brief period. This peak arises due to incremental changes in the values for flow parameters in the radionuclide transport calculations, see section 8.2.6. In general, the risk in conjunction with instantaneous flow increases is overestimated. This is particularly true for terrestrial ecosystems, where it takes time to achieve equilibrium.

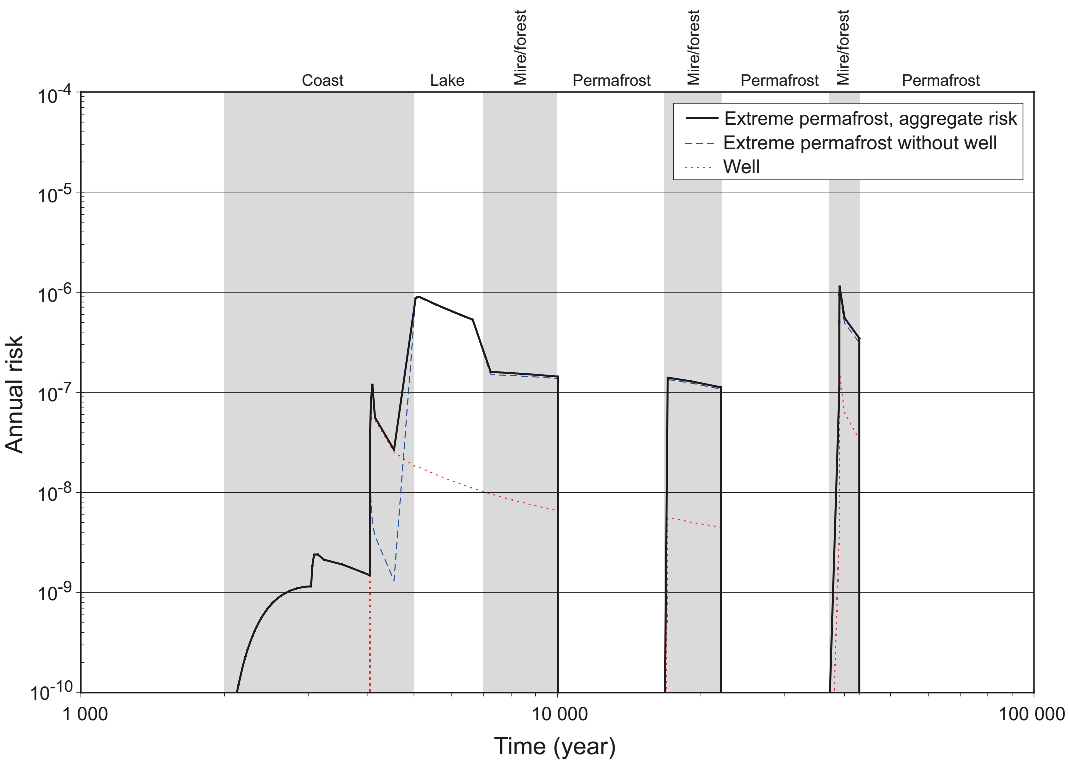


Figure 10-7. *Calculated risk for the scenario "Early freezing of the repository", the calculation cases "Extreme permafrost without well" and "Extreme permafrost with well" in the discharge area, and the aggregate risk for the scenario. Periglacial conditions with continuous permafrost prevail between 10,000 AD and 17,000 AD and between 22,000 AD and 39,000 AD, which explains the low risk during these periods. Periglacial conditions with continuous permafrost also prevail after 43,000 AD until the end of the calculation period.*

The probability of this scenario has been judged to be less than one, but since it has not been possible to assign a probability, a probability of one has nevertheless been used to calculate the risk. Based on the above considerations, the annual risk is judged to be well below 10^{-6}. The aggregate risk for the scenario "Early freezing of the repository" does not include the risk for an intrusion well, since the dose for this has not been calculated, see section 9.4.9.

10.3.3 Talik

In this scenario, the same climate evolution is posited as in the main scenario's Weichselian variant, with the difference that during periods of permafrost an unfrozen talik is formed adjacent to the repository, where groundwater can flow. This enables radionuclide transport to occur, even though continuous permafrost prevails elsewhere. The dose results show that this scenario gives the same annual doses as the main scenario's Weichselian variant up until the first permafrost period that reaches the repository occurs at 25,000 AD, see section 9.4.5. Up to this time, this scenario is identical to the main scenario's Weichselian variant. The dose maximum occurs around 5,000 AD and amounts to 12 μSv/year.

The probability of the formation of a talik adjacent to SFR 1 is assessed in section 7.6.4. The scenario is judged to be less probable than the main scenario. But it is deemed to be impossible to assign a numerical value to the probability of the scenario. A probability of one has therefore been pessimistically assumed. Risk as a function of time for the scenario "Talik" is shown in Figure 10-8.

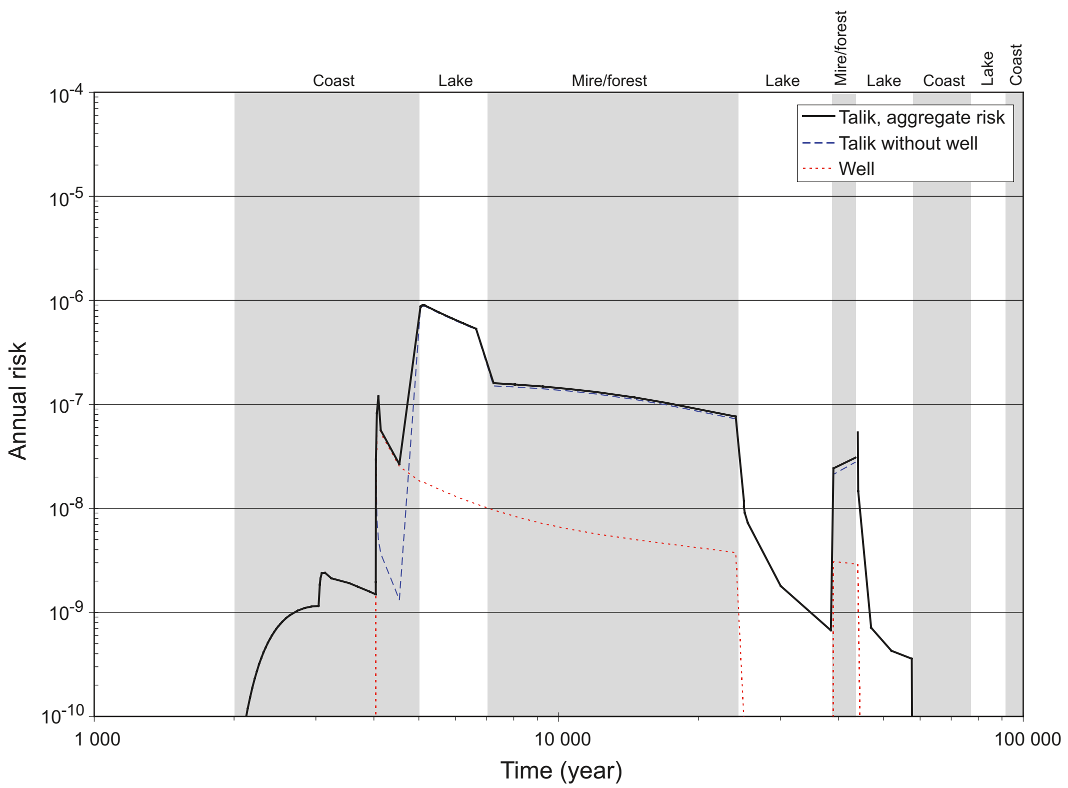


Figure 10-8. Calculated risks for the scenario "Talik without well" and "Talik with well in the discharge area", as well as the aggregate risk for the scenario. Periglacial conditions prevail between 25,000 AD and 39,000 AD and between 44,000 AD and 58,000 AD, with an unfrozen talik adjacent to the repository, where groundwater can flow. After 58,000 AD there is continuous permafrost, an ice sheet or a situation where the repository area is submerged. A period with periglacial conditions returns between 77,000 AD and 93,000 AD, but due to the talik the release goes to a lake. During the two latter periods, however, the risk is so low that it is not visible in the figure.

The scenario's highest risk without well amounts to $9 \cdot 10^{-7}$ per year and occurs in 5,000 AD. The highest risk for a well in the discharge area is the same as the highest risk for a well in the discharge area in the main scenario and occurs in 4,000 AD. The scenario's highest aggregate risk amounts to $9 \cdot 10^{-7}$ per year. The risk peak seen in Figure 10-8 in 44,000 AD occurs due to the assumption that the concrete in the barriers freezes and bursts, at the same time as a talik in the area causes the flow through the repository and the geosphere to increase. The aggregate risk for the scenario "Talik" does not include the risk for an intrusion well, since the dose for this has not been calculated, see section 9.4.9.

10.3.4 High concentrations of complexing agents

The scenario "High concentrations of complexing agents" is based on the main scenario's Weichselian variant but takes into account significantly higher concentrations of complexing agents in the near-field.

For the case without well, the highest dose occurs around 5,000 AD and amounts to 11 µSv/year. This result is based on deterministic calculations. For the case with well in the discharge area, the highest dose occurs around 4,000 AD and amounts to 19 µSv/year.

In section 7.6.5 (see also Table 7-18), the probability is assessed to be 0.1 that the assumed the concentration of complexing agents will form in the repository. This gives a highest risk for the case without well of about $8 \cdot 10^{-8}$ per year. For well in the discharge area, where another probability of 0.1 is taken into account, the highest risk is $2 \cdot 10^{-8}$ per year.

The highest doses for an intrusion well in the repository occur around 3,000 AD and amount to 820 µSv/year for the silo, 460 µSv/year for BMA, 2,100 µSv/year for 1BTF, 8,500 µSv/year for 2BTF and is unchanged compared with the main scenario for BLA (48 µSv/year), see section 9.4.9. The probability for an intrusion well is assessed in section 7.6.7 (see also Table 7-18) to be about $4 \cdot 10^{-4}$ for the silo and about $1.5 \cdot 10^{-3}$ for the rock vaults, which is combined with the probability 0.1 for the scenario "High concentrations of complexing agents". In the calculation of the risk for the intrusion well, it has been assumed to be situated in the repository part that gives the highest risk at any given time. The highest risk for intrusion well in the scenario "High concentrations of complexing agents" is $9 \cdot 10^{-8}$ per year and occurs at around 3,000 AD.

The aggregate risk for the scenario "High concentrations of complexing agents" has been calculated by adding the risk for the scenario without well to the risk for the well (in the discharge area or intrusion well) that gives the highest risk at any given time. The risks for the scenario "High concentrations of complexing agents" without well, with well in the discharge area and with an intrusion well are shown in Figure 10-9 together with the aggregate risk for the scenario. The highest aggregate risk for the scenario "High concentrations of complexing agents" is $9 \cdot 10^{-8}$ per year and occurs at around 3,000 AD.

10.3.5 Gas-driven advection

For the silo, a scenario was studied that considers the consequences of radionuclide releases resulting from expulsion of water as a consequence of gas evolution. This gas evolution takes place early, when the repository area is submerged beneath the sea, which means that the highest dose for all of SFR 1 is the same as for the main scenario and amounts to 12 µSv/year at 5,000 AD.

The probability for this scenario is set at one, see section 7.6.6 or Table 7-18. Risk as a function of time for the scenario "Gas-driven advection" is shown in Figure 10-10. The scenario's highest risk without well amounts to $9 \cdot 10^{-7}$ per year at around 5,000 AD.

A well in the repository's discharge area gives a highest risk of $1 \cdot 10^{-7}$ per year at 4,000 AD.

The highest aggregate risk for the scenario "Gas-driven advection" is $9 \cdot 10^{-7}$ per year. The aggregate risk for the scenario "Gas-driven advection" does not include the risk for an intrusion well, since the dose for this has not been calculated, see section 9.4.9.

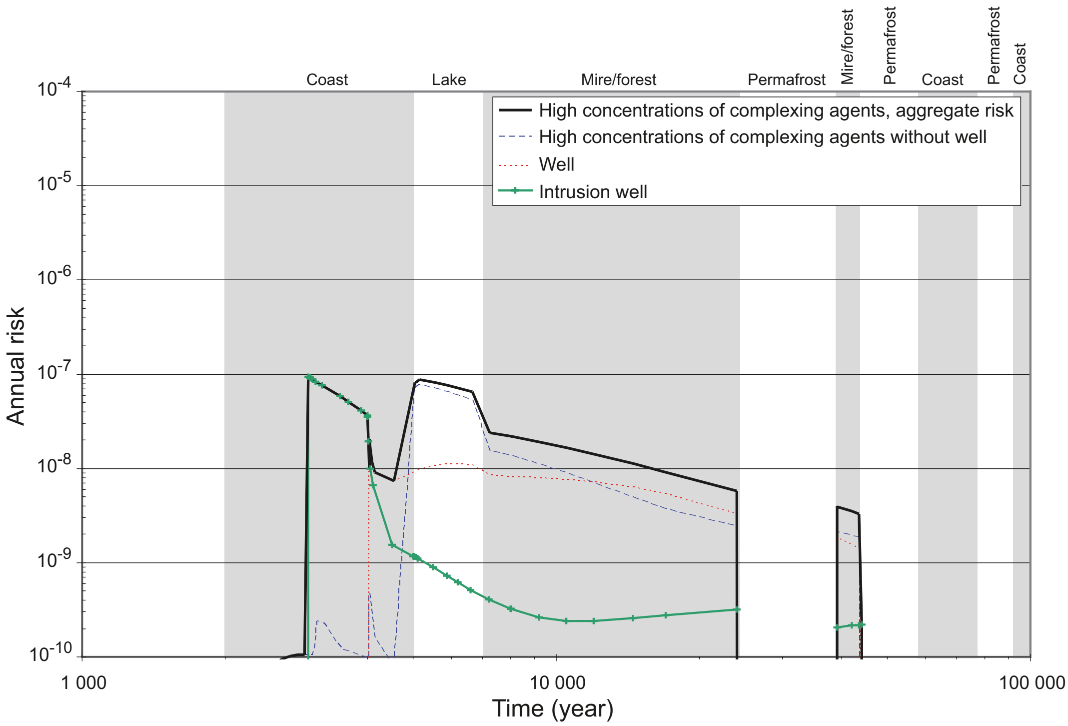


Figure 10-9. *Calculated risks for the scenario "High concentrations of complexing agents" without well, with well in the discharge area and with an intrusion well in the repository, as well as the aggregate risk for the scenario. Periglacial conditions with continuous permafrost prevail between 25,000 AD and 39,000 AD, which explains the low dose during this period. After 44,000 AD there is continuous permafrost, an ice sheet or a situation where the repository area is submerged.*

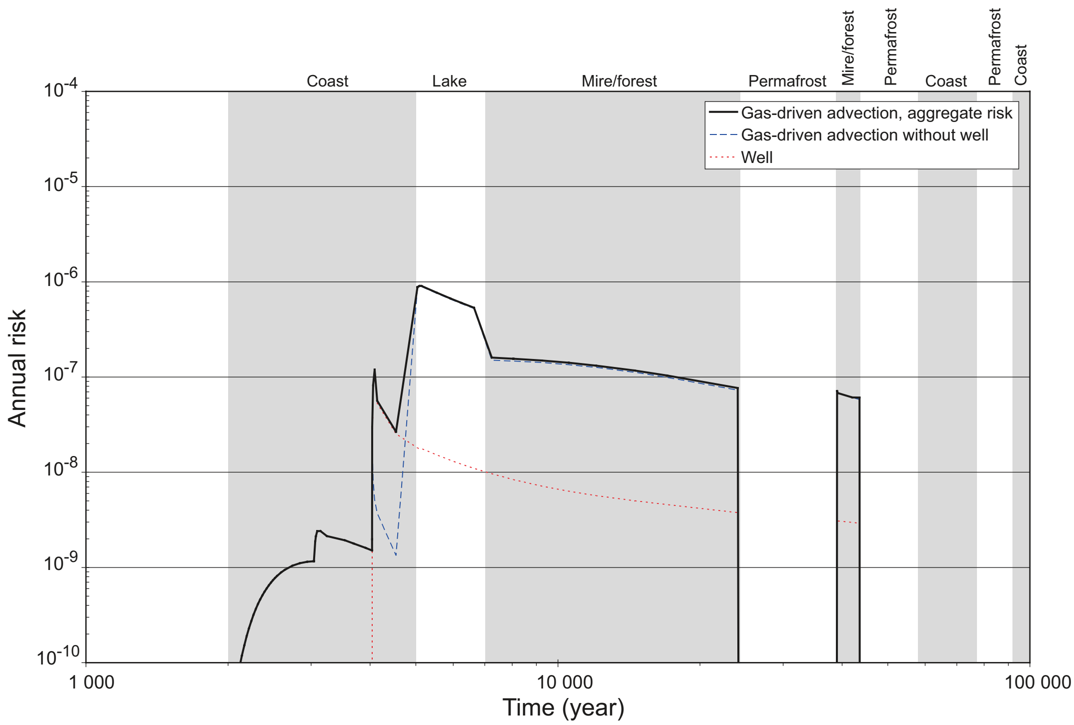


Figure 10-10. *Calculated risks for the scenario "Gas-driven advection" without well and with well in the discharge area, as well as the aggregate risk for the scenario. Periglacial conditions with continuous permafrost prevail between 25,000 AD and 39,000 AD, which explains the low dose during this period. Periglacial conditions with continuous permafrost prevail after 44,000 AD as well.*

10.3.6 Wells

The scenario "Wells" is represented by the calculation cases "Well in discharge area" and "Intrusion well in repository". Risk dilution for wells is discussed in section 10.4.

Well in discharge area

The calculation case "Well in discharge area" has been combined with the main scenario and all less probable scenarios except "Earthquake". The results are presented for each scenario in sections 10.2.2 and 10.3.2 to 10.3.5.

Intrusion well in repository

The calculation case "Intrusion well in repository" has been combined with the main scenario's Weichselian variant and the scenario "High concentrations of complexing agents". The results are presented in sections 10.2.3 and 10.3.4.

The probability for an intrusion well is estimated in section 7.6.7 (see also table 7-18) to be about $4 \cdot 10^{-4}$ for the silo and about $1.5 \cdot 10^{-3}$ for the rock vaults.

If an intrusion well is drilled, it can also cause long-term changes in the protective capability of the repository. The hydrogeological calculations carried out in the SAFE project /Holmén and Stigsson 2001a/ show that if a well has been drilled down into one of the rock vaults, this well will attract a large amount of the water from the other rock vaults. The silo, which is located further away from the rock vaults and is sealed off by more tunnel plugs, is not affected in the same way. The hydrogeological calculations show that if a well is situated in BLA, the total flow through BLA could in time increase at most to 3 to 7 times compared with the situation without a well. The flow increase could lead to increased releases, but the increase is probably exaggerated since the available groundwater recharge will scarcely be able to sustain such flows over extended lengths of time.

10.4 Risk dilution

The cumulative probability of an individual event can grow with time. In the method used to calculate risk in sections 10.2 and 10.3, no account has been taken of cumulative probability, which can lead to a risk dilution. As a complement to these risk calculations, risk calculations are presented where the cumulative probability is used to illustrate the importance of the event, as proposed in SSI's regulations SSI FS 2005:5.

To illustrate the importance of risk dilution, three events have been chosen for which risk dilution is taken into account. They are: earthquake, well in discharge area for the Weichselian variant, and intrusion well in repository for the Weichselian variant.

10.4.1 Earthquake

The risk for an earthquake of magnitude 5 or more has been calculated to illustrate the effect of risk dilution. This risk has been calculated by taking the product of the cumulative probability (i.e. the probability that an earthquake has already occurred) and the calculated dose for an earthquake that destroys the repository. The risk from the silo and BMA is illustrated in Figure 10-11.

Figure 10-11 shows that the risk compensated for risk dilution is highest for the silo for the scenario "Earthquake". The highest risk for the silo amounts to $7 \cdot 10^{-7}$ per year at 7,000 AD, as compared with $6 \cdot 10^{-7}$ per year at 5,000 AD.

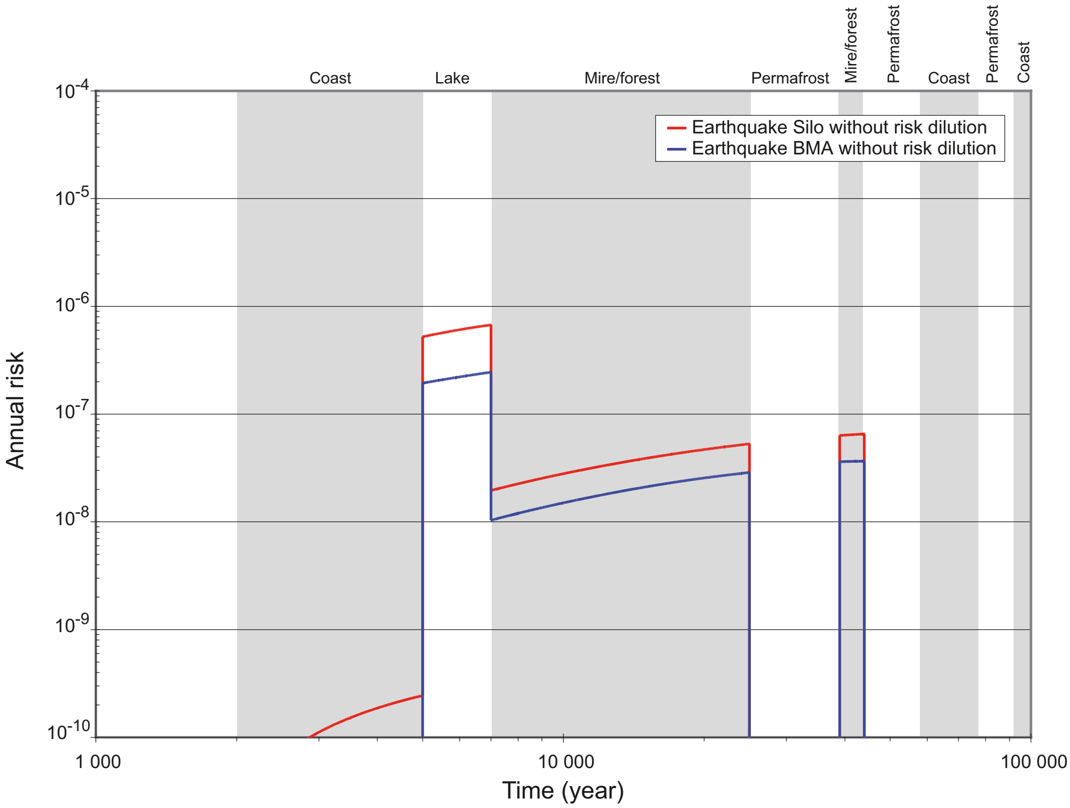


Figure 10-11. *Calculated risk compensated for risk dilution for the silo and BMA in the scenario "Earthquake". The risk has been calculated with the cumulative probability and the dose for an earthquake that destroys the repository.*

10.4.2 Well in discharge area

The consequence of a well in the repository's discharge area has been analyzed for the main scenario and most of the less probable scenarios. The fact that a well is drilled in the repository's discharge area can be regarded as an individual event which, if it occurs, can make considerable risk contributions. The probability that a well exists in the repository's discharge area at any given moment is limited. The cumulative probability that a well exists in the repository's discharge area at some time up to a given point in time can, however, be considerable during the entire studied period. The risk without risk dilution for the well in the main scenario's Weichselian variant has been pessimistically calculated by assuming that each new generation abandons all old wells and instead drills new drinking water wells with the same well frequency as that given by today's statistics for the area. The cumulative probability is calculated as follows: $P(t) = 1–(1–p)^n$, where p is the probability per generation that one of the wells is located in the discharge area and n is the number of generations that have passed. The length of a generation has been set at 30 years and p has been set at 0.1 (see section 7.6.7 or Table 7-18). Given these premises, the probability is 0.9 in about 4,700 AD.

Figure 10-12 shows that the highest risk amounts to $1 \cdot 10^{-6}$ per year at 5,000 AD. The highest risks occur early in the evolution of the repository when it is probable that the calculated cumulative probability has been overestimated with the pessimistic assumption that each generation drills new wells.

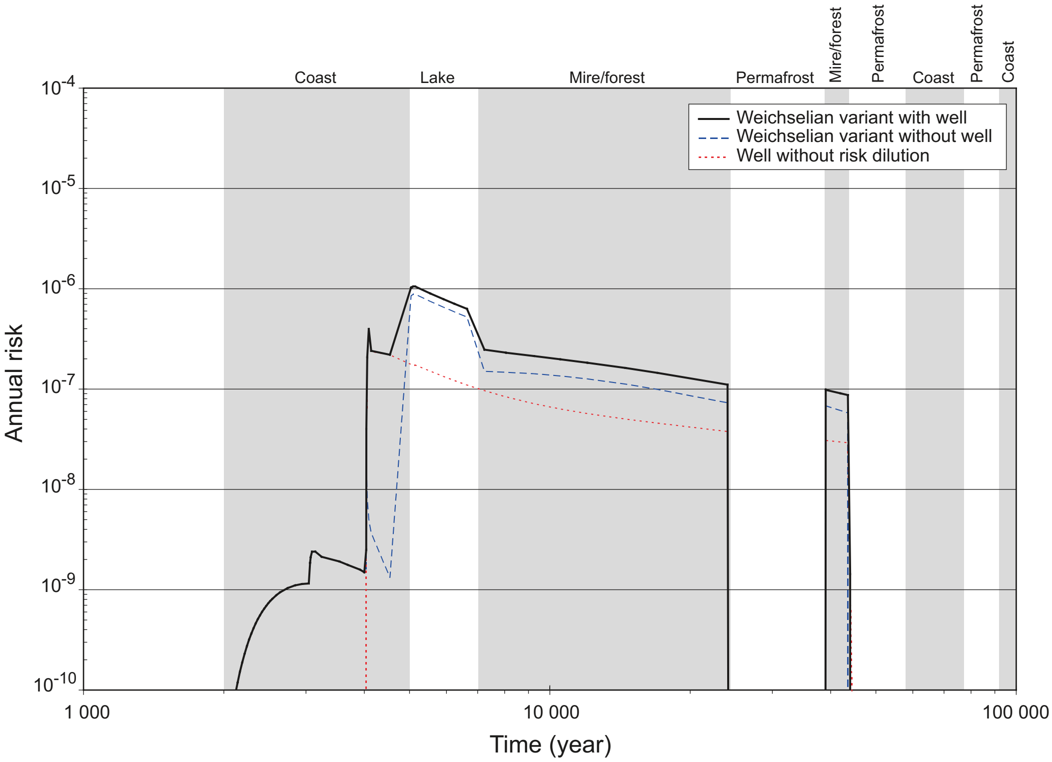


Figure 10-12. *Calculated risks compensated for risk dilution for well in the discharge area in the main scenario's Weichselian variant, the Weichselian variant without well, and the sum of these. Periglacial conditions with continuous permafrost prevail between 25,000 AD and 39,000 AD, which explains the low dose during this period. After 44,000 AD there is continuous permafrost, an ice sheet or a situation where the repository area is submerged.*

10.4.3 Intrusion well in repository

The fact that a drinking water well is drilled in the repository can be regarded as an individual event which, if it occurs, can make a considerable risk contribution. The drilling of a well in the repository at a given point in time is associated with a probability of less than one. Over an extended timespan, however, the probability that this event will occur at some time increases. The risk without risk dilution of an intrusion well in the repository has been pessimistically calculated by assuming that each new generation drills new drinking water wells according to the same method as that used in section 10.4.2. With this premise, the probability is approximately 0.73 for the silo and 0.99 for the rock vaults at 100,000 AD.

The risk for the intrusion well has been added to the risk for the main scenario's Weichselian variant without well in the repository's discharge area. In this summation, the well has always been assumed to be situated in the repository part that gives the highest risk. Figure 10-13 shows that the highest risk amounts to $1 \cdot 10^{-6}$ per year at 5,000 AD. The highest risk occurs early in the evolution of the repository when it is probable that the calculated cumulative probability has been overestimated with the pessimistic assumption that each generation drills new wells.

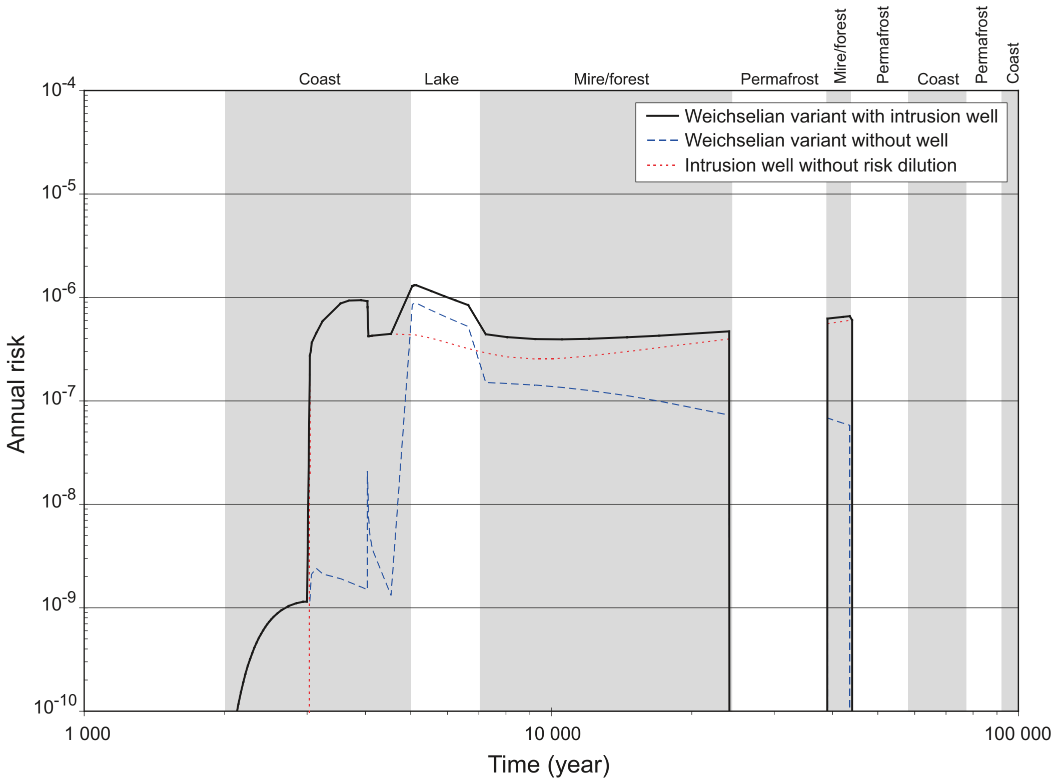


Figure 10-13. *Calculated risks compensated for risk dilution for intrusion well in the main scenario's Weichselian variant, the Weichselian variant without well, and the sum of these. In this summation, the well has always been assumed to be situated in the repository part that gives the highest risk. Before 3,000 AD, between 25,000 AD and 39,000 AD and after 44,000 AD, conditions on the site are judged to be such that a drinking water well cannot be drilled into the repository.*

10.5 Summary of risks

Based on calculated doses in Chapter 9 and probability estimates in Chapter 7, risk calculations have been done for the main scenario and the less probable scenarios. Probabilities, highest dose, highest annual risk and the time of the highest annual risk are given in Table 10-4. If a scenario has been analyzed with several calculation cases, the highest risk is shown in the table.

The risk analysis shows the following:

- For the main scenario the release is dominated by organic C-14. The highest aggregate risk amounts to $9 \cdot 10^{-7}$ per year and occurs around 5,000 AD when a lake is formed in the discharge area, after which the risk slowly declines. An intrusion well in the repository gives a lower highest risk than the main scenario without well, since the probability of such a well is low. The highest risk is obtained if the well is situated in 2BTF.
- A magnitude 5 earthquake gives the highest risk around 5,000 AD, when the risk is roughly equal to the risk for the main scenario.
- The scenario "Early freezing of the repository" shows that the estimated highest aggregate annual risk is less than $1 \cdot 10^{-6}$ at 39,000 AD, when the exposure comes from a forest ecosystem. This risk is dominated by the radionuclide I-129.
- The scenario "Talik" gives the same highest aggregate risk as the main scenario, since the highest risk occurs early in the evolution of the repository when the scenario is identical to the main scenario.

- The highest aggregate risk for the scenario "High concentrations of complexing agents" is lower than the risk for the main scenario. Intrusion well in the repository dominates the highest aggregate risk for this scenario. The highest aggregate risk amounts to $9\cdot10^{-8}$ per year and occurs at 3,000 AD.
- The highest aggregate risk for the scenario "Gas-driven advection in the repository" is the same as the risk for the main scenario. This is because the effect of gas production comes early when the doses are low due to heavy dilution, since the radionuclide release takes place to the coastal area.
- The residual scenario "Alternative inventory" is identical to the main scenario's Weichselian variant except that the inventory is approximately seven times higher. The dose for this scenario is about seven times higher than for the main scenario.
- The residual scenario "Loss of barrier function, far-field" shows that retardation through the geosphere is of little importance for the dose.
- The dose is approximately three times higher for the residual scenario "Loss of barrier function, near-field I" (no sorption in the engineered barriers) than for the main scenario. The impact on many individual nuclides is great, but the highest dose is not affected since it is dominated by organic C-14, which does not sorb in the barriers. The highest dose obtained for the residual scenario "Loss of barrier function, near-field II" (the barriers in the silo and BMA are assumed to be degraded in 5,000 AD) is approximately 30 times higher than for the main scenario. This shows how the barriers contribute to the repository's long-term safety by retarding the radionuclide releases, mainly as flow barriers.
- The residual scenario "Abandoned unclosed repository" gives a highest dose of 2,800 µSv/year 200 years after the repository has been abandoned. This dose can be compared with the natural background radiation in Sweden, which is roughly 1,000 µSv/year.
- Risk dilution has been dealt with for "Earthquake", "Well in the discharge area in the Weichselian variant" and "intrusion well in repository in the Weichselian variant" in accordance with the proposal in SSI's regulations SSI FS 2005:5. For the cases with well in the discharge area and intrusion well in the repository, the risk of 10^{-6} per year is exceeded marginally during a short period of time. For the scenario "Earthquake without risk dilution", the risk is highest for the silo. The highest risk for the silo amounts to $7\cdot10^{-7}$ per year at 7,000 AD.
- The results of calculations of concentrations of radionuclides in water and soil in the repository's environs have been compared with concentration levels at which the ERICA project deemed the impact on the environment to be negligible. The results show that the concentrations calculated to exist in the repository's environs are always several powers of ten below the concentration levels proposed by the ERICA project.
- Combinations of scenarios are discussed in section 8.5. No other combinations of scenarios than those reported in this chapter have been deemed to be possible or to contribute relevant information.

Based on the estimation of the risk for the analyzed scenarios, it is judged that the total risk from the repository will not exceed 10^{-6} per year.

The aggregate risk for each scenario is shown in Figure 10-14. Initially the risk is dominated during a short period by the scenario "Earthquake", after which it is dominated by the main scenario except for two periods which are dominated by the scenario "Early freezing of the repository".

Table 10-4. Estimated probability and highest doses for the different scenarios for the case without well in the discharge area, with well in the discharge area and with intrusion well in the repository, as well as the highest cumulative annual risks and when they occur.

Scenario category	Scenario	Probability			Highest dose (μSv/year)			Highest cumulative annual risk	Time of highest cumulative annual risk (year)
		***Without* well**	**Well in discharge area**	**Intrusion well in repository**	***Without* well**	**Well in discharge area**	**Intrusion well in repository**		
Main scenario	Weichselian variant	1	0.1	Silo: $4 \cdot 10^{-4}$Rock vaults:$1.5 \cdot 10^{-3}$	12	16	1,600	$9 \cdot 10^{-7}$	5,000
	Greenhouse variant	1	0.1		12	16		$9 \cdot 10^{-7}$	5,000
Less probable scenarios	Earthquake	Magnitude-dependent distribution over time	–		–	–		$8 \cdot 10^{-7}$	5,000
	Early freezing of the repository	< 1	0.1		13	21		$< 1 \cdot 10^{-6}$	39,000
	Talik	< 1	0.1		12	16		$< 9 \cdot 10^{-7}$	5,000
	High concentrations of complexing agents	0.1	0.1	Silo: $4 \cdot 10^{-4}$Rock vaults:$1.5 \cdot 10^{-3}$	11	19	8,500	$9 \cdot 10^{-8}$	3,000
	Gas-driven advection	1	0.1		12	16		$9 \cdot 10^{-7}$	5,000
	Wells*								
Residual scenarios	Alternative inventory	–	–	–	82	97	–	–	–
	Loss of barrier function, near-field I	–	–	–	35	110	–	–	–
	Loss of barrier function, near-field II	–	–	–	330	130	–	–	–
	Loss of barrier function, far-field	–	–	–	14	–	–	–	–
	Abandoned unclosed repository	–	–	–	2,800	–	–	–	–

* The scenario "Wells" is not reported separately, but is combined with the main scenario and other less probable scenarios.

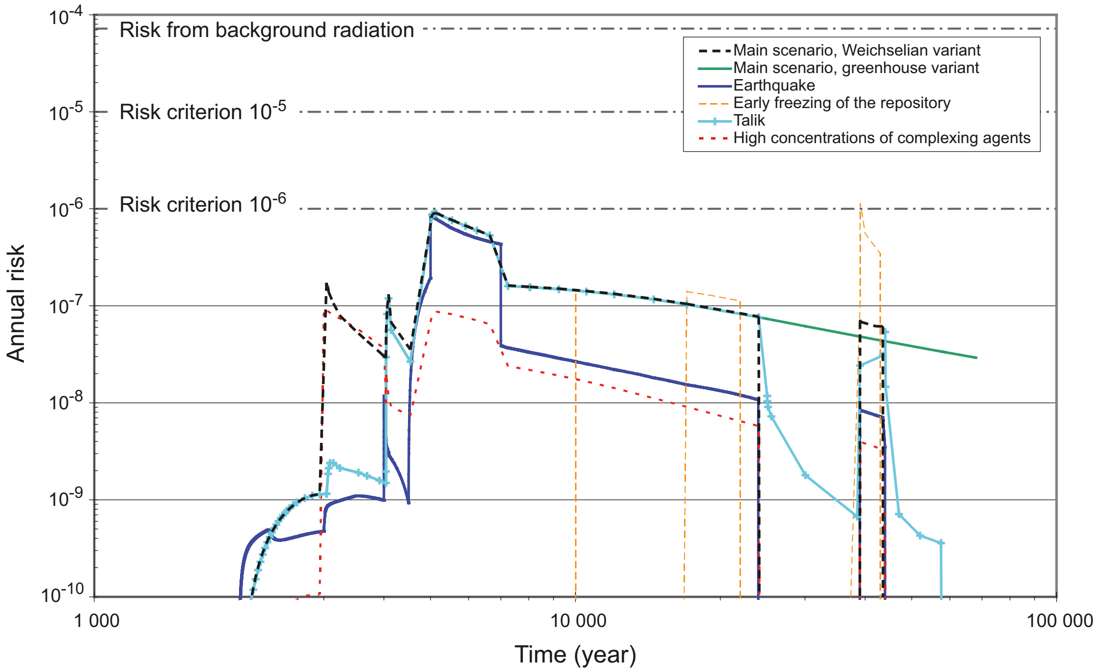


Figure 10-14. *Aggregate risk for the different scenarios. The scenario "Gas-driven advection" coincides with the main scenario's Weichselian variant and has therefore not been plotted. The risk for the scenario "Early freezing of the repository" has been calculated for a probability of one. The actual probability of the scenario cannot be estimated but is less than one.*

For the main scenario, the highest risk, $9 \cdot 10^{-7}$ per year, arises when the release from the repository goes to a lake. Productivity data for this lake show that less than thirteen persons can obtain all of their food from the lake /Bergström et al. 2008/. The risk to this group has been calculated based on the assumption that these individuals feed their entire life on organisms that have in turn lived their whole life in the lake. It has further been assumed that these persons get all their food from the lake. If food were taken from other sources as well, a lower risk would be obtained. It is more likely that people in the future as well will get their food from numerous other sources all of which are less contaminated than the food from the lake. It is further likely that a greater quantity of fish will be taken from the nearby coast than from the smaller lake, since the coast gives a greater yield. This means that the risk presented for the lake period is the maximum theoretical risk to which the most exposed individual can be exposed and that the number of individuals in the exposed group is limited. SKB therefore finds that the highest risk criterion of 10^{-5} is applicable to show that the repository complies with the regulatory risk requirement during the lake period that prevails between 5,000 AD and 7,000 AD.

10.6 Uncertainties in the risk analysis

In order to be able to judge the repository's long-term safety, it is important to have good confidence in the results. The data underlying a safety assessment are always associated with deficiencies of various kinds. Confidence presupposes a methodical management of uncertainties and deficiencies.

In brief, the uncertainties are dependent upon scenario selection, the ability of the models to describe processes with a bearing on long-term safety and how they interact, and parameter values. In Chapter 2, section 2.5, the uncertainties are divided into the following categories:

- Uncertainties associated with completeness in identification of FEPs and scenario selection
- Conceptual uncertainty
- Uncertainties in quantification of initial state
- Uncertainties in input data for calculations.

10.6.1 Completeness in identification of FEPs and scenario selection

The FEP analysis for this safety assessment was conducted in two steps. The first step was taken in the SAFE project in 2001 and covers the period up until 10,000 years after closure /SKB 2001b/. The second supplementary step has been taken with this safety assessment /Gordon et al. 2008/. In order to ensure as far as possible the completeness in the identification of FEPs, a cross-check was done in the SAFE project /SKB 2001b/ against the NEA's international database of FEPs (Version 1.0) /NEA 1997/. For the present safety assessment, the previous FEP analysis has been updated to address the regulatory authorities' viewpoints on the SAFE project /SSI/SKI 2003/ and to handle longer time periods. A cross-check was also made of identified FEPs against the FEPs arrived at for SFR by /Miller et al. 2002/ on behalf of SKI, see Chapter 3.

In order to ensure as far as possible that all relevant scenarios are taken into account in the assessment, a method (see Chapter 7) has been developed based on safety functions (see Chapter 5) and interaction matrices for the repository and the geosphere (see Chapter 3). Scenarios and descriptions of the repository system with its safety functions have been developed systematically and with the ambition of identifying all scenarios that could degrade the repository's barrier functions.

Scenarios described in the SAFE project are still relevant, but additional scenarios for the time after 10,000 AD that were not analyzed in SAFE have been identified in this safety assessment. These new scenarios derive from climate changes that take on importance in a longer time perspective, see Chapter 7. Two additional scenarios, "Earthquake" and "Abandoned unclosed repository", have been added to the scenarios that arise due to different possible climate evolutions. Earthquakes that can damage the repository's barriers become more important in the longer time perspective, and the scenario "Abandoned unclosed repository" is a response to a regulatory requirement in SKIFS 2002:1.

10.6.2 Conceptual uncertainty

The term "conceptual uncertainty" is used for uncertainties that are due either to the fact that the fundamental understanding of a process is not complete, or to the fact that a mathematical model does not correctly describe a process. The aim has been to describe all processes as realistically as possible. Where realistic assumptions cannot be supported, assumptions are instead made so that the consequences of unfavourable processes are overestimated and conversely so that the potentially positive consequences of favourable processes are underestimated or neglected. Examples of conceptual uncertainties and how they have been handled are given below.

Uncertainties in the choice of calculation premises

In dealing with uncertainties associated with necessary choices of premises in scenarios, pessimistic choices have been made in order not to underestimate the conditions for outflow of radionuclides. Furthermore, a large number of calculation cases have been studied in order to shed light on the significance of important choices in the main scenario. Consequences of different possible climate changes that can have a detrimental effect on the repository via earlier degradation of barriers have been examined. Great changes in sorption conditions via increased concentrations of complexing agents have been analyzed. Furthermore, a number of residual scenarios illustrating the consequences of hypothetical conditions have been analyzed. These residual scenarios are not included in the risk assessment, but can be used to illustrate the consequences of hypothetical losses of barrier functions and for comparison with other scenarios.

The results show that the calculation premises that have been chosen in the main scenario during most of the studied period generate risks that are higher than for other scenarios, see Figure 10-15. The scenarios that give higher risk than the main scenario during short periods are "Earthquake" and "Early freezing of the repository".

Climate change

Today it is not possible to forecast the evolution of the climate over the long time spans the safety assessment needs to cover. It is, however, highly likely that the evolution of the climate over the next 100,000 years will include periods of temperate conditions, periglacial conditions with permafrost, glaciation and transitions between these climate domains. The main scenario therefore includes these periods and transitions. The main scenario has been based on reconstructed conditions for the past 120,000 years, which includes the Weichselian glaciation and the Holocene interglacial. The main scenario also includes an alternative climate evolution with an anthropogenically increased greenhouse effect. Furthermore, two less probable scenarios, "Early freezing of the repository" and "Talik", have been studied with a number of calculation cases to show the effect of the uncertainty of future climate change.

Evolution of the surface ecosystem

The results show that it is of great importance which ecosystem will receive the releases in the future. The highest risk arises around 5,000 AD when a lake has formed in the discharge area. The transition from a coastal landscape to a lake is a slow process and there is no clear point in time when the rising coast becomes a lake in terms of, for example, water retention time. Lake formation is controlled by shoreline displacement, which means that uncertainty with regard to shoreline displacement is of great importance for the calculated highest risk. If the lake is formed earlier, the radionuclides will have less time to decay. It is not likely that the lake will come into being 1,000 years earlier than has been assumed in the calculations, but this can nevertheless provide a point of departure for estimating the consequence of earlier existence of the lake. C-14 has a half-life of around 5,700 years. If the lake is formed 1,000 years earlier than in this assessment, this means that the inventory of C-14 at the time the lake is formed is 12% higher. Provided that the groundwater flow is linked to shoreline displacement and thus does not differ between the two cases, the risk is estimated to increase by no more than 12%. This would result in a highest risk of $1 \cdot 10^{-6}$ per year for the main scenario. However, it seems unlikely that the sea level would fall faster based on today's forecasts regarding the greenhouse effect. The opposite case, that the lake is formed later, is favourable from a dose viewpoint due to greater dilution in the coastal area.

Shoreline displacement is also of importance for when wells that can be affected by the repository can be drilled, since wells cannot be drilled until the sea has withdrawn. According to statistics on existing wells /Kautsky 2001/, however, the probability that intrusion wells will be drilled earlier than about 1,000 years after the shoreline has passed the location is lower than that they will be drilled later. In this assessment, however, the same high probability has been used for an intrusion well from 3,000 AD onward.

Liberation and transport in the repository

Degradation of the engineered barriers in the repository is a slow and gradual process until, for example, the concrete freezes and bursts during a permafrost or is damaged by an earthquake. In the calculations, the properties of the barriers have changed gradually in conjunction with freezing and bursting of the concrete or erosion of the bentonite under glacial conditions. Instead of trying to describe this gradual degradation in the model for radionuclide transport, an extreme case has been analyzed. In this case, the engineered barriers in the silo and BMA degrade instantaneously in 5,000 AD, which is the time that is least favourable for the calculated risks. The results show (see scenario "Loss of barrier function, near-field II in Table 10-4) that not even such pessimistic assumptions lead to a particularly high dose.

Products from corrosion of iron and steel are not expected to have any retarding function, despite strong indications that iron oxides and iron hydroxides can sorb and co-precipitate many elements.

Inorganic C-14 in the waste that has been stabilized in cement can precipitate as calcite ($CaCO_3$). This mechanism can limit the release of inorganic C-14, but has not been taken into account in the safety assessment, see further section 10.6.5.

Transport in the geosphere

The risk calculations include the effect of retardation in the geosphere. Retardation in the geosphere reduces the risk slightly, but important nuclides such as C-14 are not appreciably affected. The importance of retardation in the geosphere is illustrated by the residual scenario "Loss of barrier function, far-field". A comparison of calculated doses for this scenario and the main scenario's Weichselian variant indicates marginal differences, see Figure 9-38. The highest dose increases to 14 µSv/year compared with 12 µSv/year for the main scenario, see Table 10-4 and Figure 9-38.

Turnover and exposure from the surface ecosystem

The radionuclide that contributes most to the highest annual doses is C-14, which is why the total uncertainty in the calculated doses is dependent on the uncertainties in the assumptions made for this radionuclide. A number of pessimistic assumptions have been made in the biosphere models used for C-14 to handle the conceptual uncertainties /Avila and Pröhl 2008/. Other assumptions made in the models are deemed to be realistic. The overall result is that the models give conservative results.

The following pessimistic assumptions have been made in the conceptual models used to calculate dose from release of C-14 to coast and lake:

- The total release of C-14 reaches the water as CO_2 or other forms that are readily taken up by primary producers.
- 100% of the release takes place during periods when it can be assimilated by photosynthesis.
- Losses resulting from release of C-14 to the atmosphere are neglected.

The following pessimistic assumptions have been made in the conceptual models used to calculate dose from release of C-14 to forest and agriculture:

- The entire release of C-14 reaches the ground-level air layer as CO_2 and can be assimilated by plants via photosynthesis.
- The height of the ground-level air layer in the model is set at the smallest possible value needed to provide plants with the carbon they need. This underestimates dilution of C-14.
- 100% of the release takes place during periods when it can be assimilated by photosynthesis.
- All C-14 that comes to agriculture via irrigation is assumed to end up in the ground-level air layer, where it can be assimilated by the irrigated plants via photosynthesis.

Another source of conceptual uncertainties, especially for radionuclides that sorb a lot in soil and sediments, is the question of where the radionuclides are assumed to enter the various ecosystems. The choice of release point that leads to the highest dose was made by comparing results with different assumptions regarding release point /Bergström et al. 2008/. For example, it was found in the calculations for a lake that release directly to the water in the lake gives the highest concentration and thereby dose. In order not to underestimate doses from the lake sediment when the lake becomes a mire, the calculations for the mire have been done for equilibrium conditions by assuming a longer release period to the mire.

In calculating the dose to individuals, pessimistic assumptions have been made regarding human habits and other premises for the calculations:

- The ecosystem that gives the highest exposure for each period is used to calculate the dose. If the ecosystem in the model consists of several biosphere objects, the biosphere object that gives the highest concentration has been used. For example, the concentrations for the coast are taken from the SAFE Basin, which comes first in the discharge area, see Figure 6-6.

- All food is assumed to come from the ecosystem that exists during the time period in question and therefore to be contaminated, which means that there is no dilution with less contaminated food. The assumption that all food is taken from the current ecosystem leads to an extreme diet, for example during lake and coastal periods when the food is assumed to consist entirely of fish and crustaceans. A more mixed diet would lead to a lower dose.
- Some radionuclides are removed during food preparation, which has not been taken into account.
- The composition of the food (for example the proportions between fish and crustaceans) is not important for the calculated dose, since it is assumed in the model that the concentration of carbon per gram is the same in all food in an ecosystem /Avila and Pröhl 2008, Bergström et al. 2008/.
- When a mire is formed it can potentially be used for agriculture or forestry. The calculations were carried out for both agriculture and forestry, and the highest doses from these alternatives were used to calculate the risk for radionuclides flowing into the mire.

Earthquake

Uncertainty in the model described in Chapter 8 to estimate radiological risk from earthquakes is assumed to be considerable, but ought to overestimate the radiological risk. It is assumed in the model that radionuclides in the repository are transported out at the exchange rate the water has if the hydrological barriers are breached. This is assumed to be pessimistic since:

- the pore network is in reality not interconnected, which means the whole radionuclide inventory will not be available for transport out of the repository,
- radionuclides are in reality assumed to sorb, which means that outward transport will be limited,
- the model assumes that the entire repository volume will be equally accessible, so that the flow will not be restricted to individual fractures,
- the transport resistance in the geosphere is completely disregarded.

Peak values and averaging

The water flows through the repository have been changed incrementally (stepwise) in the calculations, which causes peak values in the release rates /Thomson et al. 2008a/. This is not in agreement with actual conditions, where changes in the flows are mainly controlled by continuous shoreline displacement during the period up to 5,000 AD and later due to major climate changes, which are of course not instantaneous. Such peaks cause overestimation of the doses and the risks during short time periods. It is worth noting that when calculation results change quickly, this is a sign that the system reaches equilibrium quickly and that equally rapid changes in the results would not occur if the input data had changed continuously.

The peak values are thus a result of the calculation strategy used.

An example of overestimation of the risk is the case with a well in the discharge area around 4,000 AD. The calculations are therefore based on 50-year floating averages to estimate the lifetime risk that serves as a basis for the annual risk in accordance with SSI FS 2005:5, which states that "*The individual risk should be calculated as an annual average on the basis of an estimate of the lifetime risk…*".

A model for transport calculations that can describe the flow dynamics, instead of the stepwise changes in groundwater flows used here, would result in lower doses and thereby also lower risks.

10.6.3 Quantification of initial state and uncertainties in input data

Uncertainties in the quantification of the initial state result in uncertainties in input data for calculations of radionuclide transport and dose. In general, data have been chosen conservatively realistic wherever possible so that the radiological risk from the repository is not underestimated. For certain parameters that are deemed to be crucial, uncertainties have been handled by means of a probabilistic hypothesis in the models for radionuclide transport and dose calculations. This applies, for example, to sorption coefficients in different materials, flow parameters in the repository and the geosphere, and parameters for describing accumulation and uptake in the biosphere. Furthermore, a number of residual scenarios have been considered that shed light on uncertainties in the function of the engineered barriers (concrete and bentonite) and the geosphere's barrier function.

Uncertainties in the radionuclide inventory have not been included in the probabilistic calculations. The highest dose is caused by C-14 for all scenarios, except for "Early freezing of the repository" where I-129 gives the highest dose. Uncertainties in quantity estimation have been estimated to be 40% and 50%, respectively, for the nuclides that dominate the dose and the risk for the Weichselian variant without well, i.e. C-14 and Cs-135 /Torstenfelt 2007/. For a well in the discharge area and an intrusion well in the repository for the Weichselian variant, the risk is dominated by C-14, I-129 and Mo-93. The uncertainty for both I-129 and Mo-93 has been estimated to be 50% /Torstenfelt 2007/. For further discussion of uncertainties in the inventory of C-14 and their impact on the risk, see section 10.6.4. The uncertainties in the radionuclide inventory are covered by the residual scenario "Alternative inventory", except for Ag-108m and Se-79, see section 7.5.1. The uncertainty in the inventories of both Ag-108m and Se-79 is a factor of 50 /Torstenfelt 2007/. The importance of the uncertainty in the inventory of these nuclides can be assessed by estimating their contributions to the total annual dose calculated for the main scenario's Weichselian variant, see Figure 9-2. The size of these contributions shows that the uncertainty in the inventory is of no importance for the total dose and thereby for the risk as well.

The importance of the uncertainty in the biosphere parameters to the calculated doses was studied by carrying out an uncertainty and sensitivity analysis of the probabilistic calculations in the biosphere sensitivity analysis for C-14 shows that a few parameters control the calculated doses. For release to a lake, the most important parameters are the concentration of dissolved inorganic carbon in water and the net primary production, two parameters about which there is good knowledge.

The estimate of the probability for wells is based on a well density of 0.5 wells/km^2, see section 7.6.7. According to /Kautsky 2001/, the well density varies from 0.03 to 2 wells/km^2, which gives equivalent uncertainties in the risk.

The uncertainties in input data that are of importance for estimation of radiological risk from earthquakes can be divided into two categories: uncertainty in frequency and magnitude of earthquakes, and uncertainty in structural and mechanical properties of rock and repository.

Since earthquakes have only been observed instrumentally for a limited time (approximately 100 years), the body of data is limited, particularly in areas where large quakes are rare, such as in Sweden. This makes it more difficult to estimate earthquake risk, since available data must be extrapolated in order to be valid for the earthquake magnitudes and times required in the analysis. In order to compensate for this, the constants used in the Richter-Gutenberg relation to estimate earthquake models. The analysis was carried out for all radionuclides that make a significant contribution to dose. The choice of radionuclides is reported in /Bergström et al. 2008/. The results of the uncertainty and sensitivity analysis are presented in /Avila and Pröhl 2008, Bergström et al. 2008/. As shown above, C-14 is the radionuclide that makes the highest contribution to the highest annual doses and the risks in the main scenario and almost all other scenarios. The uncertainty in the calculation of dose for C-14 shows that the result for release to lake lies within a factor of 2, for coast within a factor of 5 and for forest within a factor of 20. The factors have been calculated as the ratio between the 95th and the 5th percentile.

The doses calculated for wells in the discharge area show greater variation (within a factor of 200) owing to the great variation assumed for well yield. The results of the uncertainty and frequency /Böðvarsson et al. 2006/ are based on data taken from a much larger area than the one analyzed, on historical observations of major quakes and by assuming that the repository's barriers are damaged during a glaciation in such a way that there is no point in predicting damages caused by glacially induced earthquakes.

The uncertainty in the structural and mechanical properties of rock and repository is considered to be considerable, since no studies of the mechanical strength of the repository are made in the assessment. Instead, the magnitude at which the repository is assumed to be damaged by earthquakes is based on underground facilities in different parts of the world /Bäckblom and Munier 2002/. The magnitude that is pessimistically assumed to cause damages in SAR-08 lies within an interval where no damages are normally observed, see further Chapter 7.

In summary, it can be concluded that despite the fact that great uncertainties exist related to earthquakes, the method used to describe radiological risk ought to overestimate the effect of earthquakes.

10.6.4 Uncertainties concerning C-14

For a constructive discussion of uncertainties, it is essential to focus on the uncertainties that are deemed to contribute most to the total uncertainty of the results. All results show that the highest risk occurs around 5,000 AD when outflow takes place to a lake ecosystem. During this time, organic C-14 contributes most to risk. Figure 10-15 shows the risk contributions from C-14 and from other nuclides separately for the main scenario's Weichselian variant without well.

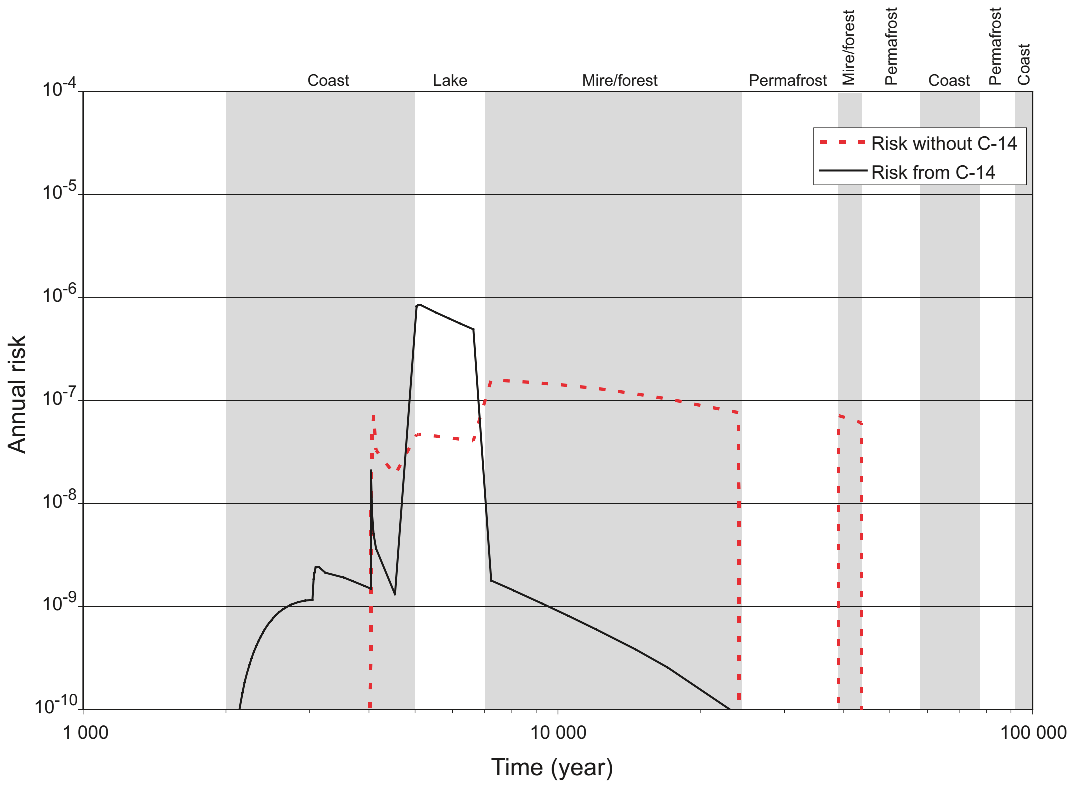


Figure 10-15. *The risk from C-14 and from other nuclides for the main scenario's Weichselian variant without well. The highest risk is clearly dominated by C-14. The highest annual risk from C-14 alone amounts to 8·10⁻⁷, while the highest aggregate annual risk from other nuclides amounts to 2·10⁻⁷.*

The highest annual risk from C-14 alone amounts to $8 \cdot 10^{-7}$, while the highest aggregate annual risk from other nuclides amounts to $2 \cdot 10^{-7}$. There is therefore reason to take a particularly close look at the different calculation premises that influence the result for C-14, such as inventory, transport properties and groundwater flow, and assumptions regarding biosphere conditions. Since C-14 has a half-life of the same order of magnitude as major changes in the biosphere (thousands of years), the time when the lake is formed is a relevant parameter.

It can be noted in Figure 10-15 that the risk from other radionuclides is not highest during the lake period. If C-14 is disregarded, the risk during both the lake period and the subsequent period with mire/forest is dominated by Cs-135 from BMA. The release of Cs-135 from the geosphere to the biosphere is relatively constant during both the lake period and the period with mire/forest. However, Cs-135 gives a lower dose for lake than for mire/forest.

Radionuclide inventory of C-14

The radionuclide C-14 in the waste is mainly produced in the reactor core and is present in the ion exchange resin found in different cleanup systems, where it occurs as either organic or inorganic carbon. The estimate of the inventory of organic C-14 is associated with uncertainties of different kinds. Firstly there is an uncertainty in the estimated quantity of waste that will be produced in the future, and secondly in the method by means of which the amount of C-14 in this waste is estimated. The first type of uncertainty is judged to be controllable and therefore of less interest; the quantity of waste that is deposited will always be known. The uncertainty that lies in the estimation of the amount of organic C-14 is, on the other hand, significant. Based on measurements /Magnusson et al. 2007/, the uncertainty in the arrived-at inventory of the total quantity of C-14 is estimated to be ± 40%. The uncertainty in the inventory of organic C-14 is judged to be slightly lower, since the upper limit of the distribution between organic and inorganic C-14 has been used. If the inventory is set at the value given by the upper uncertainty limit, 40%, a highest risk of just over $1 \cdot 10^{-6}$ per year is obtained for the main scenario.

Furthermore, there is some uncertainty in the distribution of C-14 between the repository parts. In this safety assessment, C-14 has been distributed proportionately in relation to Co-60 /Almkvist and 2007/. Work is currently being pursued at SKB aimed at a more realistic distribution.

The new distribution is based on the amount of ion exchange resin that comes with different waste streams and the measured content of C-14 in these streams. A preliminary forecast based on the new distribution indicates that the quantity of C-14 will decrease in the silo and increase slightly in BMA.

Liberation and transport of C-14 in the repository

In the inventory used in the radionuclide transport calculations, organic and inorganic C-14 has been distributed in the proportions 30/70 /Magnusson et al. 2007/. It is further assumed that all C-14 is immediately dissolved and that the assumed distribution between organic and inorganic carbon in the ion exchange resins also prevails after liberation from the waste. Organic C-14 is transported out through the waste packages and the engineered barriers without any retardation in the barriers, whereas inorganic C-14 is assumed to have some retardation in cement and the concrete barriers due to isotope exchange with calcium carbonate (calcite). The uncertainties associated with these assumptions mainly concern:

- The inventory of total C-14 in the different waste types and the distribution between the inorganic and organic forms (see above).
- Mechanisms of dissolution and liberation of C-14 from the waste.
- Redistribution between organic and inorganic carbon via degradation processes and biological carbon fixation.

- Quantification of the retardation of inorganic carbon in the barriers.
- The influence of large quantities of stable carbon in the waste.
- Groundwater flow in and around the rock vaults.

Inorganic C-14 in the waste can be dissolved in the water in the waste containers and be transported out of the containers in the form of carbonate. In cases where the waste is stabilized in cement, however, the carbonate will probably react with calcium from the cement and be precipitated as calcite ($CaCO_3$). This mechanism is not included in the quantitative analysis, but it can limit the release of inorganic C-14 from waste conditioned in cement in addition to the retardation that occurs via isotope exchange with calcite.

The liberation mechanism for organic C-14 depends on the form in which the carbon occurs in the waste. Organic C-14 is only present in the ion exchange resins from the power plants' reactor water cleanup systems. How this carbon is bound to the ion exchange resins is uncertain, but it is probably some form of chemical bond to the surface, not ion exchange /Eabry 1995/. If this is the case, the ion exchange resin should have a retaining effect in the same way as other sorbing materials in the repository. The liberation of organic C-14 thereby depends primarily on the composition of the water, which can affect how tightly C-14 is bound to the ion exchange resin. Alternatively, this easily accessible carbon can be degraded by microorganisms and in this way be liberated from the ion exchange resins /Pedersen 2001/. If C-14 is instead chemically incorporated in the organic waste material, this material must first be degraded before the radioactive carbon can be liberated, e.g. via microbial activity or other chemical processes. All of these mechanisms would lead to a lower liberation rate over a longer period of time compared with the assumption that all C-14 is immediately accessible and dissolved in the water.

If degradation of organic material leads to formation of carbon dioxide, this entails a redistribution between organic and inorganic C-14. The carbon dioxide dissolves in the water and forms calcite via reaction with calcium, which is dissolved out of the cement in the waste packages and concrete barriers. This could entail a retardation in the transport of organic C-14 out of the repository. Alternatively, any carbon dioxide that is formed can be utilized, together with hydrogen that is also formed in the repository, by methanogenic bacteria to form methane. If methane is formed and it contains C-14, this can lead to a rapid transport of organic C-14 through the near-field as well as through the geosphere.

The cement and concrete barriers in the different repository parts have been credited in the assessment with some retardation of inorganic C-14 by use of the K_d value 0.2 m^3/kg in concrete, see Table 8-6.

This is lower than can theoretically be estimated with the assumption that the retardation is caused by an isotope exchange with calcium carbonate in the barriers. A precipitation of C-14 in the form of calcite would probably lead to much greater retardation than that for which credit has been taken in the assessment. The large quantities of stable carbon in the repository also contribute strongly to the limited solubility of C-14.

The outward transport of C-14, as well as of other nuclides, is affected by the size, distribution and direction of the groundwater flow through the rock vaults. In order to take account of uncertainties in the flow through the rock vaults, flow data are handled probabilistically in the radionuclide transport model. Furthermore, several of the calculation cases are chosen to shed light on the effects of changed groundwater flow, partly due to different changes in the barrier system and partly due to climate changes that affect the flow conditions. In other words, the importance of these uncertainties is quantified in the different calculation cases.

In summary, there are both conceptual uncertainties concerning liberation and release of C-14 and uncertainties in the data used. The handling of these uncertainties in the safety assessment is judged to entail overestimation of the calculated releases from the near-field.

Turnover of C-14 in the surface ecosystem

Conceptual uncertainties and uncertainties in the choice of input data in the biosphere models for C-14 have been discussed above in section 10.6.3. In order to handle the uncertainties, pessimistic assumptions have been made that overestimate doses and risks. One possible way to reduce the uncertainties and the degree of pessimism is to develop dynamic models like the one described in /Kumblad and Kautsky 2004/.

Summary assessment of the uncertainties for C-14

The uncertainties for C-14 are judged to be associated with the nuclide inventory, liberation and transport in the repository, transport in the geosphere, and development of, cycling in and exposure from the surface ecosystem. These uncertainties have been discussed above and can be summarized as follows:

- Uncertainties in the nuclide inventory of C-14 are estimated to be ± 40%.
- There are both conceptual uncertainties concerning liberation and release of C-14 and uncertainties in the data used. The liberation mechanism for organic C-14 is not completely understood, and all C-14 has therefore been assumed to be initially available for transport. There are also other possible retarding processes that have not been taken into consideration. The importance of the uncertainties for liberation and transport in the repository have not been quantified, but the way they are handled in the safety assessment is judged to entail that the calculated releases from the near-field are overestimated.
- The uncertainty regarding transport in the geosphere is judged to have a marginal impact on the risk, since C-14 has little or negligible sorption in the geosphere. The importance of retardation in the geosphere is illustrated by the residual scenario “Loss of barrier function, far-field“. A comparison of calculated doses for this scenario and the main scenario’s Weichselian variant show marginal differences, see Figure 9-38.
- If the lake were to form earlier, it could give a marginally higher dose, but it is more probable that the lake will be formed later and that the dose reported here is overestimated.
- Several pessimistic assumptions have been made regarding turnover and exposure from the surface ecosystem, resulting in an overestimation of the risk.

A summary assessment is that the uncertainties for C-14 are handled in such a way that the calculated risk is overestimated and that the uncertainties do not lead to significant changes in the calculated risk.

11 Conclusions

The purpose of the assessment of the long-term safety of the final repository for low- and intermediate-level operational waste, SFR 1, is to show that human health and the environment are protected against ionizing radiation from the repository in a long-term perspective. The repository's long-term performance has been analyzed in detail and the results are presented in Chapters 1 to 10. This safety assessment of SFR 1 has been carried out to comply with SKI's requirement on periodic updating as well as SKI's and SSI's injunctions according to Appendix B.

11.1 Major changes compared with the preceeding safety assessment

An important difference compared with the previous safety assessment for SFR 1 /SKB 2001a/ is that much longer timespans have been considered. The screening of important features, events and processes (FEPs) has also been extended beyond 10,000 years, all the way up to 100,000 years post-closure. The systematic screening of these features, events and processes is described in Chapter 3. Climate change in particular in the long-term perspective is the main reason for changes and additions to the FEP analysis.

A new nuclide inventory has been estimated based on 50 years' operation of the nuclear power plants. This is presented in General Part 1 "Facility design and operation", Chapter 6 "Radioactive substances and waste in the facility". The new nuclide inventory is based on new waste forecasts, longer operating times at the nuclear power plants than before and new methods for estimating the quantity of difficult-to-measure nuclides in the waste. An example of this is the estimation of the quantity of C-14 in the waste. Instead of correlating with the quantity of Co-60, the quantity of C-14 has been estimated by direct measurements on ion exchange resins. Other nuclides where new methods have been developed for estimating the quantities are Cl-36, Ni-59, Ni-63, Mo-93, Tc-99, I-129 and Cs-135 /Almkvist and Gordon 2007/. The new methods contribute to reducing the uncertainty in the estimated nuclide inventory.

A first step has been taken in the work of defining safety functions for SFR 1 as a basis for the selection of scenarios. The safety function shows what role a repository component has in contributing to the safety of the repository. The safety functions are used to identify scenarios, along with the screening of FEPs presented in Chapter 3. In brief, the method for identification of scenarios entails determining, in a structured manner, what features, events and processes can cause a safety function to deteriorate, see Chapter 7.

A reference evolution has been arrived at that describes a probable evolution of the repository and its environs. The longer time perspective has necessitated a number of additions to the assessment. Thus, alternative climate evolutions with permafrost periods and glacial conditions have been considered. Longer times mean that other climatic conditions change the premises for the properties of the engineered barriers over time. For this reason, special studies have been made of the chemical degradation of concrete and bentonite over long timespans and the possible consequences of freezing of the repository. Moreover, a general study has been conducted of how permafrost periods or glacial conditions affect the hydrogeological conditions in the repository. Efforts have also been made to estimate uncertainties in important parameters in the safety assessment. Distributions have been determined for flow parameters and sorption values in different materials. The reference evolution is described in Chapter 6.

Based on the identified scenarios, calculation cases have been set up and analyzed. One difference compared with previous safety assessments is that scenarios and calculation cases have been divided into the groups main scenario, less probable scenarios and residual scenarios, in accordance with the regulatory requirements. The scenarios that have been identified in this analysis are the same as those identified in the previous safety assessment from 2001 /SKB 2001a/. In addition to the calculation cases that arise due to various possible climate evolutions, the calculation cases "Earthquake" and "Abandoned unclosed repository" have been added. Earthquakes that can damage the repository's barriers become more important in the longer time perspective, and the calculation case "Abandoned unclosed repository" is a response to a regulatory requirement in SKIFS 2002:1.

Both deterministic and probabilistic calculations have been carried out. The probabilistic calculations take uncertainties in input data into account by using distributions for input data. Flow parameters and sorption values have been treated probabilistically in the transport calculations. Numerous biosphere and exposure parameters have been treated probabilistically in the dose calculations, as in the previous assessment. A new model that better describes carbon cycling in the ecosystems has been developed and used in the dose calculations. This model is based on the specific activity approach, which is recommended by UNSCEAR and IAEA for calculating dose calculations from releases of C-14 from nuclear installations. Exposure from forest ecosystems has also been included in the dose calculations this time. Models and calculations are described in general terms in Chapter 8.

11.2 Compliance with SSI's risk criterion

The risk analysis includes calculation cases in the scenario categories "Main scenario" and "Less probable scenarios". The results show that the maximum risk over time comes from the main scenario and amounts to $9 \cdot 10^{-7}$ per year at 5,000 AD, when a lake is formed in the discharge area. The nuclide that contributes most to the risk at this time is organic C-14. This agrees with the results obtained in the safety assessment for SFR 1 from 2001 /SKB 2001a/.

Over time, the main scenario usually gives the highest risk of all scenarios. Other scenarios, such as "Earthquake" and "Early freezing of the repository", give higher risks during shorter periods, see Figure 10-14. Besides C-14, it is nuclides such as Cs-135, I-129 and Mo-93 that can make considerable contributions to the risk during certain periods. The nuclide Cs-135 dominates the risk during those periods the exposure comes from a forest ecosystem, whereas I-129 and Mo-93 are important for "well in discharge area" or "intrusion well in repository".

The results show that the radiological risk from the repository does not exceed 10^{-6} during the next 100,000 years, which is the lower of SSI's risk criteria of 10^{-6} and 10^{-5}.

11.3 Collective dose and effects on the environment

Calculations of collective dose during the first 1,000 years after closure show that the dose from C-14, which dominates the releases, is about 8 manSv, see section 9.6.

The results of calculations of concentrations of radionuclides in water and soil in the repository's environs have been compared with concentration levels at which the ERICA project /ERICA 2008/ deemed the impact on the environment to be negligible. The comparison has been made with the highest concentrations generated in the main scenario. The results show that the concentrations calculated to exist in the repository's environs are always several powers of ten below the concentration levels proposed by the ERICA project. It is therefore concluded that the repository will not affect biodiversity or sustainable use of biological resources.

11.4 General requirements on the safety assessment

SKI and SSI have in their regulations (SKIFS 2002:1, SSI FS 1998:1 and SSI FS 2005:5) stipulated requirements on the contents of a safety assessment.

In addition, SKI and SSI have also imposed requirements on SKB in the form of decisions. Appendix A and Appendix B summarize how SKB has responded to these requirements.

11.5 Possible improvements

The present safety assessment is an update of the safety assessment from 2001. The updating has been subject to regulatory requirements set forth in decisions /SKI 2007, SSI 2006/.

The biggest improvements made with this safety assessment include the development of a new method for identifying scenarios and an extension of the assessed time period to 100,000 years, which means that climate evolutions and earthquakes have been more thoroughly analyzed. Several of the changes made since previous safety assessments are summarized in section 11.1. However, since the safety assessment work is an iterative process, further areas of improvement have been identified.

It is of course important that the safety assessment be presented in a transparent manner, to facilitate the work of both conducting it and then reviewing it. To achieve this, the collected body of knowledge has been presented in dedicated background reports in a way that has now largely become standard procedure in the safety work. Future safety assessment work would be facilitated by a Data Report and a Process Report, as described below.

A number of areas of improvement are discussed in the following sections based on the method for safety assessment presented in section 2.2.

11.5.1 FEP processing (system understanding)

The FEP report that was produced for the preceding safety assessment of SFR 1 has been augmented to cover the extended time period for the assessment. Since the FEP analysis for this safety assessment has been carried out in two steps, they are presented in different reports. In conjunction with the next safety assessment, an updated report with a summary of the state of knowledge concerning FEPs may be necessary.

11.5.2 Initial state

The nuclide inventory is of great importance for the results of the safety assessment. Already in the preceding safety assessment, uncertainties in the inventory of C-14 and the liberation and transport of this nuclide in the repository were mentioned as a source of uncertainty for the risk from the repository. Uncertainties in the transport of C-14 were linked to uncertainties in groundwater flow in and around the rock vaults.

In the present safety assessment, the total inventory of C-14 has been determined by measurements on ion exchange resins, an improvement compared with the previous method of correlation with Co-60. However, in this assessment the distribution of C-14 between repository parts is done on the basis of the distribution of Co-60. Work is currently being pursued at SKB aimed at better describing the distribution of C-14 based on the amount of ion exchange resin from different waste streams.

The nuclide inventory presumes that the nuclear power plants are in operation for 50 years. After the radionuclide transport calculations had been concluded, some nuclear power plants decided to extend their operating time to 60 years. This decision has therefore not been taken into consideration. But just like today, SKB's future forecasts for waste quantities will always be based on the best information available at the time.

11.5.3 Safety functions and selection of scenarios

A new method for identifying scenarios has been used for SFR 1. This method is based on a set of safety functions developed in this safety assessment and the interaction matrices for the repository and the geosphere. The purpose of the method is to identify scenarios in a structured and transparent manner.

The safety functions that have been identified and the method used have proved to be practical and to provide good support in the work of identifying scenarios. An evaluation of the method and the selected safety functions will be done for the next safety assessment.

11.5.4 Reference evolution

A limited system understanding has made it necessary to describe certain processes in a simplified and pessimistic manner. Better knowledge of the processes that take place and the conditions that prevail in the repository would make it possible to reduce the degree of conservatism/pessimism in the assessment.

The knowledge that exists in numerous background reports concerning the evolution of the repository and its environs has not been described in discipline-specific process reports.

Instead, the process reports for SR-Can have been utilized to a great extent. Instead of having the state of knowledge presented in separate background reports, it would have been an advantage to have repository-specific process reports where, for example, concrete degradation and the chemical conditions in the repository could be described in a more coherent way.

11.5.5 Radionuclide transport and dose calculations

The choice of input data for the radionuclide transport and dose calculations should be presented in a transparent manner to facilitate the work of both conducting the safety assessment and then reviewing it. No new data report has been produced, since the necessary data already existed for the most part in the data report for the previous safety assessment for SFR 1 /SKB 2001c/ and in the data report for SR-Can /SKB 2006c/. A smaller quantity of data has also been taken directly from other background reports for the present safety assessment for SFR 1. Future safety assessment work would be facilitated by the publication of a new data report.

In the calculations carried out to show that SFR 1 complies with SSI's risk criterion, the description of how the repository and its environs evolve has been made as reasonable as possible and uncertainties in input data have been handled probabilistically. As a result, the calculation cases analyzed are fairly comprehensive. Based on the knowledge obtained from these calculations, a number of possible supplementary calculation cases have been identified. The purpose of these calculation cases is to improve our understanding of how individual processes in the modelled system influence the final risk by using simpler and more focused calculations.

The effect of earthquakes has been described with a simple model based on pessimistic assumptions. However, no analysis has been made of the repository's ability to withstand earthquakes. Instead, a literature review has been conducted showing that the repository is expected remain intact in the face of earthquakes with a magnitude of less than 5, see section 7.6.1.

In order to enable the risk from a repository subjected to an earthquake to be estimated with greater certainty, the next safety assessment should include an analysis of the resistance of the different repository parts. The assessment would also benefit from the development of models used to describe the transport of radionuclides out of the repository as a result of an earthquake.

11.6 Confidence in the results of the safety assessment

The results show that the highest risks are obtained for the main scenario (and the scenarios that coincide with the main scenario during the first lake period) as well as the scenarios "Earthquake" and "Early freezing of the repository". The scenario "Early freezing of the repository" gives a high risk late in the evolution of the repository, around 40,000 AD.

It has not been possible to quantify the probability of this scenario, so a probability of one has been used to calculate risk. But in reality the probability of the scenario is less than one, so the actual risk is lower. The scenario "Earthquake" gives a highest annual risk of about $9 \cdot 10^{-7}$ around 5,000 AD. The scenario "Earthquake" is described with a simplified calculation model based on pessimistic assumptions. A more refined model would probably give a lower highest risk for the scenario.

For the main scenario, the highest risk, $9 \cdot 10^{-7}$ per year, arises when the release from the repository goes to a lake. The calculated risk is highly dependent on the type of ecosystem that receives the release and the size of the risk is strongly linked to the formation of the lake. The calculated highest risk is dominated by C-14. Uncertainties in the safety assessment regarding C-14 are discussed in section 10.6.5 and are judged to have been handled in such a way that the risk is not underestimated. Productivity data for the lake show that fewer than thirteen persons can obtain all of their food from the lake /Bergström et al. 2008/. The risk presented for the lake period is the maximum theoretical risk to the most exposed individual, see discussion in section 10.5. It is assumed that the individuals in the exposed group get all their food from the lake so that there is no dilution with uncontaminated food. It is therefore deemed unlikely that the risk would be higher than the one calculated here.

11.6.1 Bounding cases

Even if confidence in the results of the assessment is high, the possibility cannot be entirely ruled out that some harmful phenomenon might exist that is unknown today. The consequences of the possibility that something might have been overlooked have been studied in three residual scenarios. In these residual scenarios, the consequences of disregarding transport resistance in the near- and far-field or of assuming that the engineered barriers do not perform as intended anymore are examined. This could occur in situations where the sorption and hydraulic properties of the barriers are much worse than expected.

The residual scenario that gives the highest dose is the case where the engineered barriers in the repository degrade already in 5,000 AD, which means that both the chemical and the hydraulic properties of the concrete and bentonite barriers deteriorate instantaneously. 5,000 AD has been chosen because it is the time at which the consequences of failed barriers are greatest. The result of this scenario is a highest dose of 330 μSv per year. This highest dose occurs when the barriers fail and can be compared with the natural background radiation in Sweden, which is roughly 1,000 μSv per year.

11.6.2 Uncertainties

In the discussion of confidence it is important to consider the question of the completeness of the assessment and how uncertainties have been handled. In brief, the uncertainties are dependent upon scenario selection, the ability of the models to describe processes with a bearing on long-term safety and how they interact, and parameter values. The following uncertainties are discussed in section 10.6:

- *Completeness in identification of FEPs and scenario selection*
  In order to ensure as far as possible the completeness in the identification of FEPs, a cross-check was done in the SAFE project /SKB 2001a/ against the NEA's international database of FEPs (Version 1.0) /NEA 1997/. In the supplementary FEP analysis a cross-check was made against the FEPs arrived at for SFR on behalf of SKI /Miller et al. 2002/. In order to ensure as far as possible that all relevant scenarios are taken into account in the assessment, a method (see Chapter 7) has been developed based on safety functions (see Chapter 5) and the interaction matrices for the repository and the geosphere (see Chapter 3).

- *Conceptual uncertainty*
  The term "conceptual uncertainty" is used for uncertainties that are due to the fact that the fundamental understanding of a process is not complete, or to the fact that a mathematical model does not correctly describe a process. The aim has been to describe all processes as realistically as possible. But where realistic assumptions cannot be supported, assumptions are made so that the consequences of unfavourable processes are overestimated and conversely so that the potentially positive consequences of favourable processes are underestimated or neglected. A number of examples are given in section 10.6.2.

- *Quantification of initial state and uncertainties in input data*
  In general, data have been chosen cautiously realistically so that the risk from the repository is not underestimated. For certain parameters, uncertainties have, where possible, been handled by means of a probabilistic hypothesis in the models for radionuclide transport and dose calculations. This applies, for example, to radionuclide sorption coefficients for different materials, flow parameters in the repository and the geosphere, and parameters for describing accumulation and uptake in the biosphere. Furthermore, residual scenarios have been considered that shed light on the performance of the engineered barriers (concrete and bentonite) and the geosphere.

- *Uncertainties concerning C-14*
  The highest risk from the repository is dominated by C-14 and occurs when the release from the repository goes to a lake that is formed in the discharge area in 5,000 AD. Uncertainties associated with C-14 and the calculated dose from this lake are therefore important to estimate in order to gain confidence in the results of the assessment. The uncertainties are associated with the nuclide inventory of C-14, liberation and transport in the repository, and development of, cycling in and exposure from the surface ecosystem. These uncertainties are discussed in detail in section 10.6.

11.6.3 Conclusion

In the light of the above discussion of confidence, SKB concludes that the assessment that has been presented shows that SFR 1 fulfils the criteria for final disposal of radioactive waste that have been established by the Swedish Nuclear Power Inspectorate and the Swedish Radiation Protection Authority, and that SFR 1 therefore does not pose any future radiological risk to man and the environment.

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Appendix A

Relevant regulations and how they are handled in the present safety assessment

Summary

This appendix (referred to in Chapter 1) describes the application of

- SKIFS 2002:1 "The Swedish Nuclear Power Inspectorate's Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste",
- SSI FS 1998:1 "The Swedish Radiation Protection Institute's Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste",
- SSI FS 2005:5 "The Swedish Radiation Protection Authority's guidelines on the application of the regulations (SSI FS 1998:1) concerning protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste".

Sections that are not dealt with or are not applicable in the present safety assessment are shaded in grey.

SKIFS 2002:1

The Swedish Nuclear Power Inspectorate's Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste, issued on 24 October 2001.

Pursuant to sections 20 a and 21 of the Ordinance (1984:14) on Nuclear Activities, the Swedish Nuclear Power Inspectorate has issued the following regulations and decided on the following general recommendations.

Application

Section 1 These regulations apply to facilities for the disposal of spent nuclear fuel and nuclear waste (final repositories). The regulations do not apply to facilities for shallow ground burial of low-level nuclear waste in accordance with section 19 of the Ordinance (1984:14) on Nuclear Activities. The regulations contain supplementary provisions to the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

Barriers and their Functions

Section 2 Safety after the closure of a repository shall be maintained through a system of passive barriers.

Section 3 The function of each barrier shall be to, in one or several ways, contribute to containing, preventing or retarding the dispersion of radioactive substances, either directly, or indirectly by protecting other barriers in the barrier system.

Handling in the present safety assessment: *The barriers in SFR 1 and their contribution to safety is described in brief in section 2.4 "Safety principles" and in more detail in Chapter 5 "Safety functions", where the function of the barriers is also described. The barriers in each of the different repository parts are described in section 4.2 "Design and closure of the repository" and in General Part 1 "Facility design and operation", section 3.3.1 "Barriers and safety functions" and Chapter 5 "Facility and function description".*

Section 4 A deficiency in any of the repository's barrier functions that is detected during the construction or operation of the repository and that can lead to a deterioration in post-closure safety beyond what is predicted in the safety report shall be reported to the Swedish Nuclear Power Inspectorate without delay. The same applies if suspicion arises of such a deficiency or of the possibility that such a deficiency might arise in the future.

Design and construction

Section 5 The barrier system shall be able to withstand such features, events and processes that can affect the post-closure performance of the barriers.

Handling in the present safety assessment: *The sturdiness of the barriers must stand in proportion to the radiotoxicity of the waste over time. The main purpose of the safety assessment is to show this.*

Section 6 The barrier system shall be designed and constructed taking into account the best available technology.

Handling in the present safety assessment: *The facility is designed in accordance with the regulatory framework in effect when the facility was built. In connection with future extensions, major facility alterations and closure, BAT will be applied and optimization against calculated risk will be implemented.*

Section 7 The barrier system shall comprise several barriers so that, as far as possible, the necessary safety is maintained in spite of a single deficiency in a barrier.

Handling in the present safety assessment: *It is shown in several calculation cases in Chapter 9 "Radionuclide transport and dose calculations" that safety is maintained despite deficiencies in the barriers. The effect of degraded barriers is shown already in the main scenario. The calculations in section 9.5 "Calculation cases for residual scenarios" show the effect of partial or complete loss of certain barriers.*

Section 8 The impact on safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analyzed and reported to the Swedish Nuclear Power Inspectorate.

Safety assessment

Section 9 In addition to the provisions of Chapter 4 section 1 of the Swedish Nuclear Power Inspectorate's Regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities, the safety assessments shall also cover features, events and processes which can lead to the dispersion of radioactive substances after closure, and such analyses shall be made before repository construction, before repository operation and before repository closure.

Handling in the present safety assessment: *The systematic screening of features, events and processes is described in Chapter 3 "Identification, prioritization and handling of FEPs".*

Section 10 A safety assessment shall cover as long a time span as barrier functions are required, but at least ten thousand years.

Handling in the present safety assessment: *An account of the time periods that are of importance for SFR 1 is given in section 2.3 "Time periods". The present safety assessment covers the period up to 100,000 years after closure of SFR 1.*

Safety analysis report

Section 11 The safety analysis report for a final repository shall, in addition to what is required in Chapter 4 section 2 of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities, contain the information required in Appendix 1 of these regulations that concerns the time after closure.

Prior to repository closure, the final safety analysis report must be renewed and undergo safety review in accordance with Chapter 4 section 3 of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) Concerning Safety in Certain Nuclear Facilities and must be reviewed and approved by the Swedish Nuclear Power Inspectorate.

Exceptions

Section 12 The Swedish Nuclear Power Inspectorate may, if special reasons exist, grant exceptions from these regulations if this can be done without departing from the purpose of the regulations and on condition that safety can be maintained.

Appendix 1 of SKIFS 2002:1

The following shall be reported with regard to analysis methods:

- How one or several methods have been used to describe the passive system of barriers in the repository, its performance and evolution over time; the method or methods shall contribute to providing a clear picture of the features, events and processes that can affect the performance of the barriers and the interactions between these features, events and processes.

Handling in the present safety assessment: *The method used is summarized in Chapter 2 "Method" and further elaborated on in Chapter 3 "Identification, prioritization and handling of FEPs", Chapter 5 "Safety functions", Chapter 6 "Reference evolution for the repository and its environs" and Chapter 7 "Selection of scenarios".*

- How one or more methods have been used to identify and describe relevant scenarios for sequences of events and conditions that can affect the future evolution of the repository; the scenarios shall include a main scenario that takes into account the most probable changes in the repository and its environs.

Handling in the present safety assessment: *The method for identification of scenarios is described in Chapter 7 "Selection of scenarios".*

- The applicability of models, parameter values and other premises used for description and calculation of repository performance as far as reasonably achievable.

Handling in the present safety assessment: *The applicability of the models used is discussed in the Model Summary Report /SKB 2008/. The applicability of parameter values is described in the data reports for the SAFE project /SKB 2001c/ and SR-Can /SKB 2006c/ as well as a number of background reports (see section 2.7.1 "Data selection") where other premises are also discussed.*

- How uncertainties in the description of barrier functions, scenarios, calculation models and calculation parameters as well as variations in barrier properties have been handled in the safety assessment, including the reporting of a sensitivity analysis which shows how the uncertainties affect the description of the evolution of the barriers and the analysis of the consequences for human health and the environment.

Handling in the present safety assessment: *A general description of handling of uncertainties is given in section 2.5 "Uncertainty management" and a more detailed description is given in background reports. Probabilistic calculations are carried out to deal with uncertainties in parameter values. A sensitivity analysis on the parameter level is presented in the background report "Dose assessments for SFR 1" /Bergström et al. 2008/. Uncertainties in the description* *of the future evolution of the repository are addressed by analysis of a number of scenarios identified in Chapter 7 "Selection of scenarios". Validation studies of the calculation models are summarized in the Model Summary Report /SKB 2008/.*

The following shall be reported with respect to the analysis of post-closure conditions:

- The safety assessment in accordance with section 9 comprising descriptions of the evolution of the biosphere, the geosphere and the repository for selected scenarios; the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

Handling in the present safety assessment: *A reasonable example of the evolution of the final repository, the geosphere and the biosphere is described in Chapter 6 "Reference evolution for the repository and its environs". Alternative evolutions are described in Chapter 7 "Selection of scenarios". The final repository's environmental impact is described in Chapter 9 "Radionuclide transport and dose calculations" and Chapter 10 "Assessment of risk".*

Excerpts from SKI's general recommendations concerning SKIFS 2002:1

The Swedish Nuclear Power Inspectorate's General Recommendations concerning the Application of the Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste (SKIFS 2002:1)

Following is an unabridged excerpt of recommendations that are relevant to sections 9 and 10 and the appendix in SKIFS 2002:1, in other words the parts that concern the safety assessment.

On section 9 and Appendix

The safety of a repository after closure is analyzed quantitatively, primarily by estimating the possible dispersion of radioactive substances and how they are distributed in time for a relevant selection of future possible sequences of events (scenarios). The purpose of the safety assessment is to show, inter alia, that the risks from these scenarios are acceptable in relation to the requirements on the protection of human health and the environment issued by the Swedish Radiation Protection Authority (SSIFS 1998:1). The safety assessment should also aim at providing a basic understanding of the performance of the final repository in different time periods and at identifying requirements regarding the performance and design of different repository components.

A *scenario* in the safety assessment comprises a description of how a given combination of external and internal conditions affect repository performance. Two groups of such conditions are:

- external conditions in the form of features, events and processes which occur outside repository barriers; this includes climate changes and their impact on the repository environs, such as permafrost, glaciation, land subsidence and land uplift, as well as effects of human activities,
- internal conditions in the form of features, events and processes which occur inside the repository; this includes properties, including defects, of nuclear material, nuclear waste and engineered barriers and related processes, as well as properties of surrounding rock and related processes.

Based on an analysis of the probability of occurrence of different types of scenarios in different time periods, scenarios with a significant impact on repository performance should be divided into different categories:

- main scenario,
- less probable scenarios,
- other scenarios or residual scenarios.

The main scenario should be based on the probable evolution of external conditions and realistic or, where justified, pessimistic assumptions with respect to the internal conditions. It should comprise future external events that have a significant probability of occurrence or that cannot be shown to have a low probability of occurrence during the time covered by the safety assessment. Furthermore, it should be based as far as possible on credible assumptions with respect to internal conditions, including substantiated assumptions concerning the occurrence of manufacturing defects and other imperfections, which allow for an analysis of the repository's barrier functions (it is, for example, not sufficient to always assume that the waste containers remain leaktight for a long time, even if this can be shown to be the most probable case). The main scenario should be used as the starting point for an analysis of the impact of uncertainties (see below), which means that the analysis of the main scenario also includes a number of calculation cases.

Less probable scenarios should be prepared for evaluation of scenario uncertainty (see also below). These include variants of the main scenario with alternative sequences of events as well as scenarios that take into account the impact of future human activities such as damage inflicted on barriers. (Injuries to humans intruding into the repository are covered by residual scenarios, see below). Analysis of less probable scenarios should include analysis of uncertainties that are not evaluated within the framework of the main scenario.

Residual scenarios should include sequences of events and conditions that are selected and studied independently of probabilities in order to shed light on the importance of individual barriers and barrier functions. The residual scenarios should also include cases to shed light on injuries to humans intruding into the repository as well as cases to shed light on the consequences of an unclosed repository that has been left unmonitored.

Handling in the present safety assessment: *The method for selection of scenarios and the selected scenarios are presented in Chapter 7 "Selection of scenarios".*

A lack of knowledge and other uncertainties in the calculation premises (assumptions, models, data) are denoted in this context as *uncertainties*.

These uncertainties can be classified as follows:

- scenario uncertainty: scenario uncertainty: uncertainty in external and internal conditions with respect to type, degree and time sequence,
- system uncertainty: system uncertainty: uncertainty as to the completeness of the description of the system of features, events and processes used in the analysis of both individual barrier functions and the performance of the repository as a whole,
- model uncertainty: uncertainty in the calculation models used in the analysis,
- parameter uncertainty: uncertainty in the parameter values (input data) used in the calculations,
- spatial variation in the parameters used to describe the barrier functions of the rock (primarily with respect to hydraulic, mechanical and chemical conditions).

There are often no clear borderlines between the different kinds of uncertainties. The important thing is that the uncertainties are described and handled in a consistent and structured manner.

The evaluation of uncertainties is an important part of the safety assessment. This means that uncertainties should be discussed and considered thoroughly in both the selection of calculation cases, calculation models and parameter values and the assessment of calculation results.

Handling in the present safety assessment: *A general description is given in section 2.5 "Uncertainty management". Probabilistic calculations are carried out to deal with uncertainties in certain parameter values. Uncertainties in the description of the future evolution of the repository are addressed by analysis of a number of scenarios identified in Chapter 7 "Selection of scenarios". Uncertainties and the importance of uncertainties are discussed in Chapter 10 "Assessment of risk".*

The assumptions and calculation models that are used should be chosen carefully in view of the application and the choice should be justified by discussion of alternatives and references to the scientific literature. In cases where there is doubt as to which model is applicable, several models should be used to shed light on the effects of the uncertainty in the choice of model.

Handling in the present safety assessment: *The applicability of the calculation models used is discussed in the Model Summary Report /SKB 2008/. Calculation assumptions are described in background reports, see section 1.3.1 "Important background reports for long-term safety" and Table 1-1 "The most important background reports for judging the long-term safety of SFR 1".*

Both deterministic and probabilistic methods should be used so that they complement each other and in this way give as comprehensive a risk picture as possible. The probabilities that scenarios and calculation cases will actually occur should be estimated as far as possible to permit risk calculation. Such estimates cannot be exact. Consequently, the estimates should be substantiated by the use of several methods, for example, assessments by several independent experts. This can be done, for example, by estimations of when different events can be expected to have occurred.

Handling in the present safety assessment: *Deterministic and probabilistic methods are used for calculation of hydrogeology, radionuclide transport and dose calculations. Assessment of probability is dealt with in Chapter 7, "Selection of scenarios", and calculation of risk in Chapter 10, "Assessment of risk".*

Based on scenarios that can be shown to be particularly important from a risk standpoint, a number of *design basis cases* should be identified. These cases, together with other information on for example manufacturing method and controllability, should be used to substantiate design premises such as requirements on barrier properties.

Handling in the present safety assessment: *The preliminary safety assessment for SFR 1 that was submitted with the application for a permit to build SFR 1 showed that the design of the barriers was adequate. No design basis cases have been analyzed for the existing facility. Design basis cases will be presented prior to extension and closure of SFR.*

Particularly in the case of disposal of nuclear material, for example spent nuclear fuel, it should be shown that criticality cannot occur in the initial configuration of the nuclear material. With respect to the redistribution of the nuclear material by means of physical and chemical processes, which can lead to criticality, it should be shown that such a redistribution is very improbable.

The results of calculations in the safety assessment should contain such information and should be presented in such a way that an overall assessment of safety compliance with the requirements can be made.

Handling in the present safety assessment: *The final calculated risk is presented in Chapter 10 "Assessment of risk" compiled in a table.*

The validity of the assumptions used, such as models and parameter values, should be verified by e.g. references to scientific literature, special investigations and research results, laboratory experiments on different scales, field tests and studies of natural phenomena (natural analogues).

Handling in the present safety assessment: *The validity of calculation models is examined in the Model Summary Report /SKB 2008/. The safety assessment verifies the validity of assumptions and parameter values by reference to scientific literature etc.*

Scientific background material and expert assessments should be documented in a traceable manner by references to scientific literature and other background material.

Handling in the present safety assessment: *All scientific background material to the safety analysis report that consists of first-order references is referred to in a traceable manner. These references are found in one of SKB's document management systems (SKBdoc and e-library), are publicly available publications (for example books or scientific articles) and are included in the safety analysis report belonging to the reference binder.*

On section 10

The time period for which safety has to be maintained and demonstrated should be a starting point for the safety assessment. One way to discuss and justify the choice of such a time period is by comparing the toxicity of the radioactive content of the repository with the toxicity of radioactive substances in natural deposits. However, it should also be possible to take into consideration the difficulties of conducting meaningful analyses for extremely long time periods, beyond one million years, other than by showing how the radiotoxicity of the radionuclides in the repository declines with time.

In the case of a repository for long-lived waste, the safety assessment may have to include scenarios which take into account major expected climate changes, primarily in the form of future glaciations. For example, the next complete glacial cycle, which is currently estimated to be on the order of 100,000 years, should be particularly taken into account.

Handling in the present safety assessment: *An account of the time periods that are of importance for SFR 1 is given in section 2.3 "Time periods". The radiotoxicity of the waste is discussed in section 1.2.2 "The toxicity of the waste".*

For periods up to 1,000 years after closure, in accordance with the provisions of SSIFS 1998:1, the dose and risk calculated for today's conditions in the biosphere constitute the basis for the assessment of the safety and protective capability of the final repository.

Furthermore, for longer periods, the assessment can be made using dose as one of several safety indicators. This should be taken into account in connection with calculations as well as the presentation of analysis results. Examples of such supplementary safety indicators are the concentrations of radioactive substances from the repository which can accumulate in soils and near-surface groundwater or the calculated flow of radioactive substances to the biosphere.

(See also SSIFS 1998:1 and SSI's comments on those regulations.)

Handling in the present safety assessment: *Radionuclide transport calculations for the repository and the geosphere are presented in a separate background report /Thomson et al. 2008a/. Dose calculations are presented in Chapter 9 "Radionuclide transport and dose calculations". Concentrations of radioactive substances in soil and near-surface groundwaters are reported in Chapter 10 "Assessment of risk".*

SSI FS 1998:1

The Swedish Radiation Protection Institute's Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste; issued on 28 September 1998.

On the basis of sections 7 and 8 of the Radiation Protection Ordinance (1988:293), the Swedish Radiation Protection Institute has issued regulations as follows.

> Section 1 These regulations apply to the final management of spent nuclear fuel and nuclear waste. The regulations do not apply to facilities for shallow ground burial of low-level nuclear waste in accordance with section 19 of the Ordinance (1984:14) on Nuclear Activities.

Definitions

Section 2 In these regulations the following concepts are used with the meanings specified here:

best available technology: the most effective measure available to limit the release of radioactive substances and the harmful effects of the releases on human health and the environment, which does not entail unreasonable costs,

intrusion: human intrusion into a repository which can affect its protective capability,

optimization: keeping the radiation doses to humans as low as reasonably achievable, economic and social factors taken into account,

harmful effects: cancer (fatal and non-fatal) as well as hereditary effects in humans caused by ionizing radiation, in accordance with paragraphs 47–51 in Publication 60, 1990, of the International Commission on Radiological Protection 60, 1990,

protective capability: the capability to protect human health and the environment from the harmful effects of ionizing radiation,

final management: handling, treatment, transportation, interim storage prior to, and in connection with, final disposal as well as the final disposal,

risk: the product of the probability of receiving a radiation dose and the harmful effects of the radiation dose.

Terms and concepts used in the Radiation Protection Act (1988:220) and the Act (1984:3) on Nuclear Activities have the same meanings in these regulations.

Holistic approach etc

Section 3 Human health and the environment shall be protected from the harmful effects of ionizing radiation during the time when the various stages of the final management of spent nuclear fuel or nuclear waste are being implemented as well as in the future. The final management may not cause impacts on human health and the environment outside Sweden's borders that are more severe than those accepted inside Sweden.

Handling in the present safety assessment: *Dose to man and the environment outside Sweden's borders is discussed in Chapter 9 "Radionuclide transport and dose calculations". The various handling steps for management of nuclear waste are dealt with through the entire the safety assessment.*

Section 4 Optimization must be achieved and the best available technology shall be taken into consideration in the final management of spent nuclear fuel and nuclear waste.

Handling in the present safety assessment: *The facility is designed in accordance with the regulatory framework in effect when the facility was built. In connection with future extensions, major facility alterations and closure, BAT will be applied and optimization against calculated risk will be implemented. Optimization in connection with the disposal of waste is described in SFR 1 SAR in General Part 1 "Facility design and operation", section 5.3.2 "Optimization of operation in SFR 1".*

The collective dose as a result of the expected outflow of radioactive substances during a period of 1,000 years after closure of a repository for spent nuclear fuel or nuclear waste shall be calculated as the sum, over 10,000 years, of the annual collective dose. The calculation shall be reported in accordance with sections 10–12.

Handling in the present safety assessment: *The collective dose is calculated in Chapter 9 "Radionuclide transport and dose calculations".*

Protection of human health

Section 5 A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk. (Facilities in operation are subject to the Swedish Radiation Protection Institute's regulations (SSI FS 1991:5, amended 1997:2) concerning the limitation of releases of radioactive substances from nuclear power plants and the Swedish Radiation Protection Institute's regulations (SSI FS 1994:2, amended 1997:3) concerning health physics for activities involving ionizing radiation at nuclear facilities.)

The probability of harmful effects as a result of a radiation dose shall be calculated using the probability coefficients provided in Publication 60, 1990, of the International Commission on Radiological Protection.

Handling in the present safety assessment: *Assessment of risk and of compliance with the risk criterion is one of the main purposes of the present safety assessment. An initial description of how risk is handled is provided in section 2.6 "Risk management" and the final risk evaluation is presented in Chapter 10 "Assessment of risk".*

Environmental protection

Section 6 The final management of spent nuclear fuel and nuclear waste shall be implemented so that biodiversity and a sustainable use of biological resources are protected against the harmful effects of ionising radiation.

Section 7 Biological effects of ionizing radiation in affected habitats and ecosystems shall be described. The account shall be based on available knowledge of the affected ecosystems and shall take particular account of the existence of genetically distinctive populations such as isolated populations, endemic species and species threatened with extinction and any other organisms worth protecting.

Handling in the present safety assessment: *The concentrations of the various radionuclides in the relevant media, such as soil and water, have been calculated. An account is given of this in Chapter 10 "Assessment of risk".*

Intrusion and access

Section 8 A repository shall be primarily designed with respect to its protective capability. If measures are adopted to facilitate access or hinder intrusion, the effects on the protective capability of the repository shall be described.

Section 9 The consequences of intrusion into a repository shall be described for the different time periods mentioned in sections 11–12. The protective capability of the repository after intrusion shall be described.

Handling in the present safety assessment: *The repository's protective capability is analyzed with reference to the planned closure method described in section 4.2 "Design and closure of the repository". The consequences of intrusion in the final repository are discussed in section 9.5 "Residual scenarios". The repository's protective capability after intrusion has not been analyzed specifically, but is discussed with reference to other results, see Chapter 9 "Radionuclide transport and dose calculations".*

Time periods

Section 10 An assessment of a repository's protective capability shall be reported for two time periods of orders of magnitude specified in sections 11–12. The description shall include a case which is based on the assumption that the biospheric conditions which exist at the time when an application for a permit to construct the repository is submitted will not change. Uncertainties in the assumptions made shall be described and taken into account in the assessment of protective capability.

The first thousand years following repository closure

Section 11 For the first thousand years following closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the effects on human health and the environment.

Period after the first thousand years following repository closure

Section 12 For the period following the first thousand years after repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the evolution of the repository's properties, its environment and the biosphere.

Handling in the present safety assessment: *An account of the time periods that are of importance for SFR 1 is given in section 2.3 "Time periods". Dose consequences for different time periods and scenarios are described in Chapter 9 "Radionuclide transport and dose calculations".*

Exceptions

Section 13 If special reasons exist, the Swedish Radiation Protection Institute may allow exceptions from these regulations.

SSI FS 2005:5 Guidelines on the application of SSI FS 1998:1

The Swedish Radiation Protection Authority's guidelines on the application of the regulations (SSI FS 1998:1) concerning protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste; issued on 5 September 2005.

Guidelines concerning geological disposal of spent nuclear fuel and nuclear waste

On section 1. Area of application

These guidelines are applicable to final geological disposal of spent nuclear fuel and nuclear waste. The guidelines cover measures that are undertaken with a view to develop, site, construct, operate and close a repository and that can affect the protective capability of the repository and environmental consequences after closure.

The guidelines are also applicable to the measures that are undertaken with spent nuclear fuel and nuclear waste before final disposal and that can affect the protective capability of the repository and environmental consequences after closure. This includes activities at other facilities such as the conditioning of waste that takes place by grouting of waste in concrete and by encapsulation of spent nuclear fuel, as well as transportation between facilities and direction of waste to different repositories, including near-surface repositories for low-level nuclear waste that are licensed in accordance with section 19 of the Ordinance (1984:14) on Nuclear Activities. However, the guidelines, like the regulations, are not applicable to the near-surface repository itself.

On section 2: Definitions

Terms used in the Radiation Protection Act (1988:220), the Act (1984:3) on Nuclear Activities and SSI's regulations on protection of human health and the environment in connection with final management of spent nuclear fuel and nuclear waste have the same meaning in these guidelines. In addition, the following definitions are used:

Scenario:	A description of the possible evolution of the repository given an initial state, and conditions in the environment and their evolution.
Exposure pathway:	The migration of the radioactive substances from a repository to a point where human beings or any organism covered by the environmental protection regulations are present. This includes dispersion in the geological barrier, transport with water and air flows, migration in ecosystems and uptake in human beings or organisms in the environment.
Risk analysis:	An analysis aimed at clarifying the protective capability of a repository and its consequences with regard to environmental impact and risk for human beings.

On sections 4, 8 and 9: Holistic approach etc and intrusion and access

Optimization and Best Available Technology

The regulations require that optimization shall be implemented and that best available technology shall be taken into account. Optimization and best available technology should be employed in parallel with a view to improving the protective capability of the repository.

Optimization of a repository entails that measures should be evaluated on the basis of calculated risks.

Application of best available technology in connection with final disposal means that the siting, design, construction, operation and closure of the repository and appurtenant system components should be carried out so as to prevent, limit and delay releases from both engineered and geological barriers as far as is reasonably achievable. In considering different measures, an overall assessment should be made of their impact on the protective capability of the repository.

In cases where considerable uncertainty is associated with the calculated risks, for example in analyses of the repository long after closure, or analyses made at an early stage of the development work with the repository system, greater weight should be placed on best available technology.

In the event of conflicts between optimization and best available technology, priority should be given to best available technology.

Experience from risk analyses and the development work with the repository should be exploited for optimization and to ensure use of the best available technology.

Handling in the present safety assessment: *In connection with future extensions, major facility alterations and closure, BAT will be applied and optimization against calculated risk will be implemented. Optimization in connection with the disposal of waste is described in SFR 1 SAR in General Part 1 "Facility design and operation", section 5.3.2 "Optimization of operation in SFR 1.*

Collective dose

The regulations require an account of the collective dose from releases that take place during the first thousand years after closure. For final disposal, the collective dose should also be used in comparisons between alternative repository concepts and sites. The collective dose need not be reported if the repository concept entails a complete isolation of the spent nuclear fuel or the nuclear waste in engineered barriers during the first thousand years after closure.

Handling in the present safety assessment: *Collective dose is reported in Chapter 9 "Radionuclide transport and dose calculations".*

Occupational radiation protection

An account should be given of measures undertaken for radiation protection of workers that may have a negative impact on the protective capability of the repository or make it more difficult to assess.

Handling in the present safety assessment: *For information on occupational radiation protection, see General Part 1 "Facility design and operation", section 7.2.5 "Dose load to personnel".*

Future human impact and the preservation of information

In applying best available technology, consideration should also be given to the possibility of reducing the probability and consequences of inadvertent future human impact on the repository, for example inadvertent intrusion. Increased repository depth and avoidance of sites with extractable mineral assets may, for example, reduce the probability of inadvertent human intrusion.

Handling in the present safety assessment: *The probability of inadvertent intrusion is deemed to decrease due to the depth of the repository in combination with a low probability of the occurrence of mineral deposits in the area /Lindroos et al. 2004/. The results of a consequence analysis of intrusion in the repository are reported in Chapter 9 "Radionuclide transport and dose calculations".*

Preservation of knowledge about the repository could reduce the risk of future human impact. A strategy for preservation of information should be conceived so that measures can be taken before closure of the repository. Examples of types of information that should be preserved are the location of the repository, its content of radioactive substances and its design.

Handling in the present safety assessment: *Work on information preservation for SFR has been pursued at SKB and is described in the report "Kunskapshantering på SKB" /SKB 2003/, of which SKI and SSI have previously been informed. A project is under way at SKB dealing with SKB's future knowledge preservation.*

On sections 5–7: Protection of human health and the environment

Risk to an individual from the general public

The relationship between dose and risk

According to the regulations, the recommendations of the International Commission on Radiological Protection (ICRP) are to be used for calculation of the harmful effects of ionizing radiation. According to ICRP publication no. 60, 1990, the factor for conversion of effective dose to risk is 7.3 percent per sievert.

The regulatory criterion for individual risk

According to the regulations, the risk of harmful effects for a representative individual in the group exposed to the greatest risk (the most exposed group) shall not exceed 10^{-6} per year. Since the most exposed group cannot be described in an unambiguous way, the group should be regarded as a way of quantifying the protective capability of the repository.

One way of defining the most exposed group is to include the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk. If a larger number of individuals can be considered to be included in such a group, the arithmetic average of individual risks in the group can be used for demonstrating compliance with the criterion for individual risk in the regulations. One example of such an exposure situation is a release of radioactive substances into a large lake that can be used as a source of drinking water and for fishing.

If the exposed group only consists of a few individuals, the regulatory criterion for individual risk can be considered to be complied with if the highest calculated individual risk does not exceed 10^{-5} per year. An example of a situation of this kind might be if consumption of drinking water from a drilled well is the dominant exposure path. In such a calculation example, the choice of individuals with the highest risk load should be justified by information about the spread in calculated individual risks with respect to assumed living habits and places of sojourn.

Handling in the present safety assessment: *SSI's recommendation for conversion factor between dose and risk and definition of the most exposed group is applied. Furthermore, the risk criterion 10^{-5} per year is applied when the exposed group consists of a few individuals. An account of the risk calculations is given in Chapter 10 "Assessment of risk".*

Averaging risk over a lifetime

Individual risk should be calculated as an annual average on the basis of an estimate of the lifetime risk for all relevant exposure pathways for each individual. Lifetime risk can be calculated as the accumulated lifetime dose multiplied by the conversion factor of 7.3 per cent per sievert.

Handling in the present safety assessment: *Individual risk is calculated according to the method recommended above and described in Chapter 10 "Assessment of risk".*

Averaging risk between generations

Deterministic and probabilistic calculations can both be used to illustrate how risk from the repository evolves with time. A probabilistic analysis can, however, in certain cases provide an inadequate picture of how a single event that damages the final repository, such as a major earthquake, affects the risk for a single generation. The probabilistic calculations should in this case be supplemented as specified in Appendix 1.

Handling in the present safety assessment: *This is taken into consideration in the assessment and is described in Chapter 9 "Radionuclide transport and dose calculations".*

Selection of scenarios

The assessment of the protective capability and environmental consequences of the repository should be based on a set of scenarios that together illustrate the most important sequences of events for the evolution of the properties of the repository, its environs and the biosphere.

Handling of climate evolution

In view of the great uncertainties associated with the assumptions regarding climate evolution in a remote future and in order to facilitate the interpretation of the risk to be calculated, the risk analysis should be simplified to include several possible climate evolutions.

A realistic set of biosphere conditions should be associated with each climate evolution. The different climate evolutions should be selected so that they together illustrate the most important and reasonably foreseeable sequences of future climate domains and their impact on the protective capability and environmental consequences of the repository. The choice of the climate evolutions that serve as a basis for the analysis should be based on a combination of sensitivity analyses and expert judgements. Additional guidance is provided in the guidelines to sections 10–12.

The risk from the repository should be calculated for each assumed climate evolution by weighing together the risk contributions from a number of scenarios that together illustrate how the more or less probable sequences of events in the repository and the surrounding rock affect the repository's protective capability and environmental consequences. The calculated risk should be reported and evaluated separately for each climate evolution in relation to the regulations' criterion for individual risk. It should thus be possible to show that the final repository complies with the risk criterion for the alternative climate evolutions. If a lower probability than one (1) is given for a particular climate evolution, this should be backed up by, for example, expert statements.

Handling in the present safety assessment: *Three different climate evolutions, corresponding to those used in SR-Can /SKB 2006c/, are taken into account and assessed against the risk criterion.*

Future human impact

A number of scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository and some examples of other activities that indirectly lead to a deterioration in the protective capability of the repository, for example by changing the hydrological or hydrogeochemical conditions in the repository or its environs. The selection of intrusion scenarios should be based on present-day living habits and technology and take into consideration the properties of the repository.

The consequences of the repository's disturbed protective capability should be illustrated by calculations of the doses for individuals in the most exposed group, and reported separately and independently of the risk analysis for the undisturbed repository. The results should be used to shed light on conceivable countermeasures and to provide a basis for the application of best available technology (see guidelines on optimization and best available technology).

No account of the direct consequences for the individuals intruding into the repository is necessary.

Handling in the present safety assessment: *Future human impact is taken into account in the form of wells drilled near the repository and directly into the repository. The consequence of ingestion of water from these wells is taken into account as well as the consequence of irrigation in the scenario with a well in the discharge area, see Chapter 9 "Radionuclide transport and dose calculations". However, the possible impact of these wells on the continued protective capability of the repository is not considered.*

Special scenarios

For repositories primarily based on containment of the spent nuclear fuel or nuclear waste, an analysis of a conceivable loss of one or more barrier functions of key importance for the repository's protective capability during the first thousand years after closure should be made separately and independently of the risk analysis. The purpose of such an analysis should be to clarify how the different barriers contribute to the protective capability of the final repository.

Handling in the present safety assessment: *The purpose of SFR's barriers is to retard radionuclide transport rather than to contain the radionuclides. Residual scenarios demonstrate the function of barriers, see Chapter 9 "Radionuclide transport and dose calculations".*

Biosphere conditions and exposure pathways

The future biosphere conditions for calculations of consequences for human beings and the environment should be selected so that they agree with the climate domain that is assumed to prevail. Unless it is clearly unreasonable, however, today's biosphere conditions at the repository and in its environs should be evaluated, i.e. agricultural land, forest, wetland (mire), lake, sea or other relevant ecosystems. Furthermore, consideration should be given to land uplift (or subsidence) and other predictable changes.

The risk analysis can include a limited selection of exposure pathways, but the choice of these exposure pathways should be based on an analysis of the diversity of human use of environmental and natural resources which can occur in Sweden today. Consideration should also be given to the possibility of individuals being exposed to combinations of exposure pathways within and between different ecosystems.

Handling in the present safety assessment: *The approach described above has been applied, see Chapter 9 "Radionuclide transport and dose calculations".*

Environmental protection

The above description of exposure pathways should also include exposure pathways to certain organisms in the ecosystems that are mentioned above and that should be included in the risk analysis. The concentration of radioactive substances in soil, sediment and water should be reported where this is relevant for the respective ecosystem.

When a biological effect for the identified organisms can be presumed, an evaluation should be made of the consequence this may have for the affected ecosystems for the purpose of facilitating an assessment of the impact on biological diversity and a sustainable use of the environment.

The analysis of consequences for organisms in "today's biosphere" carried out as described above should be used for the assessment of environmental consequences in a long-term perspective. For assumed climates where today's biosphere conditions are obviously unreasonable, for example a colder climate with permafrost, it is sufficient to make a rough analysis based on knowledge of relevant ecosystems available today. Additional guidelines are given in Appendix 2.

Handling in the present safety assessment: *The concentrations of the various radionuclides in the relevant media, such as soil and water, have been calculated. An account is given of this in Chapter 10 "Assessment of risk.*

Reporting of uncertainties

Identification and assessment of uncertainties in, for instance, site-specific and generic data and models should be done in accordance with the instructions given in general recommendations from the Swedish Nuclear Power Inspectorate. The different categories of uncertainties that are specified there should be evaluated and presented in a systematic way and evaluated with reference to their importance for the results of the risk analysis. The account should also include an explanation of the methods selected for handling different types of uncertainties, for example in connection with the selection of scenarios, models and data. All calculation steps with associated uncertainties should be described.

Peer review and expert panel elicitation can, in cases where the basic data is insufficient, be used to strengthen the credibility of assessments of uncertainties in matters of great importance for the assessment of the protective capability of the repository.

Handling in the present safety assessment: *An account is given of handling of uncertainties in section 2.5 "Uncertainty management." Uncertainties are further discussed in Chapter 9 "Radionuclide transport and dose calculations", Chapter 10 "Assessment of risk" and Chapter 11 "Conclusions".*

On sections 10–12: Time periods

Two time periods are defined in the regulations: the period up to a thousand years after closure and the time thereafter.

For longer time periods, the results of the risk analysis should be progressively regarded more as an illustration of the protective capability of the repository given certain assumptions.

The following principles should provide guidance for the limitation of the risk analysis in time:

1. For a repository for spent nuclear fuel or other long-lived nuclear waste, the risk analysis should cover at least approximately one hundred thousand years or the period for a glacial cycle to shed light on reasonably predictable external stresses on the repository. The risk analysis should thereafter be extended in time as long as it provides important information about the possibility of improving the protective capability of the repository, but no longer than for a time span of up to one million years.

2. For other repositories for nuclear waste than those referred to in point 1, the risk analysis should cover at least the time until the expected maximum consequences regarding risk and environmental impact have occurred, but no longer than a time span of up to one hundred thousand years.

The arguments for the selected limitations of the risk analysis should be presented.

Handling in the present safety assessment: *SFR is a repository for short-lived radioactive waste for which an analysis period of no more than 100,000 years is recommended. The analysis period in the present safety analysis report is 100,000 years, see section 2.3 "Time periods".*

Account for the first thousand years after closure

The designation of a thousand years should be regarded as the approximate time period for which a risk analysis can be carried out with high credibility with regard to factors such as climate and biosphere conditions. For this time period, available measurement data and other knowledge about the initial conditions should be used for a detailed analysis and account of the evolution of the protective capability of the repository and its environs.

Conditions and processes during the early evolution of the repository that can affect its long-term protective capability should be described particularly thoroughly. Examples of such conditions and processes are resaturation of the repository, stabilization of hydrogeological and geochemical conditions, thermal evolution and other transient sequences.

Biosphere conditions and known trends in the environs of the repository should also be described in detail, partly to be able to characterize "today's biosphere" (see guidelines to section 5), and partly to be able to characterize the conditions that may exist in connection with a conceivable early release from the repository. By "known trends" is meant here, for example, land uplift (or subsidence), possible trends in the climate evolution and associated changes in use of land and water.

Handling in the present safety assessment: *The approach described above is applied. The first 1,000 years are described and analyzed in greater detail, see the reference evolution in Chapter 6 "Reference evolution for the repository and its environs.*

Account for very long time periods

Up to one hundred thousand years

The account should be based on a quantitative risk analysis in accordance with the guidelines to sections 5-7. Supplementary indicators of the repository's protective capability – such as barrier functions, radionuclide fluxes and concentrations in the environment – should be used to strengthen the credibility of the calculated risks.

The designation of one hundred thousand years is approximate and should be selected in such a way that the effect of expected large climate changes, for instance, a glacial cycle, on the protective capability of the repository and consequences for the environs can be illustrated.

Handling in the present safety assessment: *The approach described above is applied, see the reference evolution in Chapter 6 "Reference evolution for the repository and its environs", Chapter 9 "Radionuclide transport and dose calculations" and Chapter 10 "Assessment of risk".*

Beyond one hundred thousand years

The risk analysis should illustrate the long-term evolution of the repository's barrier functions and the importance of major external disturbances to the repository such as earthquakes and glaciations. Taking into consideration the increasing uncertainties over time, the calculation of doses to man and the environment should be done in a simplified way with respect to climate evolution, biosphere conditions and exposure pathways. The climate evolution can be described in simplified terms as a repetition of identical glacial cycles.

A strictly quantitative comparison of calculated risk with the regulatory criterion for individual risk is not meaningful. The assessment of the protective capability of the repository should instead be based on a discussion of the calculated risk combined with several supplementary indicators of the protective capability of the repository such as barrier functions, radionuclide fluxes and concentrations in the environment. If the calculated risk exceeds the regulatory criterion for individual risk or if there are other indications of substantial disturbances of the protective capability of the repository, the underlying causes of this should be explained, along with possible measures to improve the protective capability of the repository.

Handling in the present safety assessment: *See section 2.3 "Time periods".*

Summary of arguments for compliance with the regulatory requirements

An account should be given of how the principles for optimization and best possible technology have been applied in the siting and design of the repository with associated system components and how quality assurance has been used in the work with the repository and associated risk analyses.

Handling in the present safety assessment: *The quality assurance work is described in section 2.7 "Documentation and quality assurance". The facility is designed in accordance with the regulatory framework in effect when the facility was built. In connection with future extensions, major facility alterations and closure, BAT will be applied and optimization against calculated risk will be implemented.*

The arguments for the protective capability of a repository should be evaluated and presented in a systematic way. The account should include a logically structured argument for the protective capability of the repository with information on calculated risks, uncertainties in calculations and reasonability in assumptions. In order to provide a good understanding of the results of the risk analysis, the way in which individual scenarios contribute to the risk from the repository should be made clear.

Handling in the present safety assessment: *The entire safety assessment comprises a systematic analysis of the protective capability of the repository. Calculated risk is presented in Chapter 10 "Assessment of risk". Uncertainties are discussed in Chapter 9 "Radionuclide transport and dose calculations", Chapter 10 "Assessment of risk" and Chapter 11 "Conclusions".*

Appendix B

Handling of the regulatory authorities' decisions concerning long-term safety since SAFE in the present safety assessment

This appendix is referred to in Chapter 1. In a similar manner to what has been done in Appendix A, a review is conducted here of the regulatory authorities' decisions regarding the safety assessment of SFR 1, taken after the previous safety analysis (SAFE) was finished. The regulatory authorities' decisions are presented together with comments regarding how the decisions have been handled in the present safety assessment.

Relevant regulatory decisions:

- SKI decision dated 2003-12-22: Additional conditions needed from a safety viewpoint for Svensk Kärnbränslehantering AB's permit of 22 June 1983 to build, own and operate a final repository for low- and intermediate-level waste in Forsmark.
- SKI decision dated 2007-06-08: Supplement to safety assessment for the final repository for low- and intermediate-level waste, SFR 1.
- SSI decision dated 2003-12-08: Request for supplementary accounts pertaining to SKB's safety report for SFR 1.
- SSI decision dated 2006-02-27: Injunction on reporting.

Requirements	Handled	Comment SKB
SKI 2003-12-22 Dnr.7.49/011030		
The safety report shall be supplemented with a coherent safety concept (safety strategy) for SFR 1 that sheds light on the priorities of different analyses that have been done and how the requirements on barriers are met at different times.	Yes	An overall safety concept is described in section 2.4. The repository's safety functions are presented in section 5.3, and Chapter 6 shows how the safety functions are fulfilled for the reference evolution during different time periods. The areas that have been prioritized for further analysis in this safety assessment are described in section 1.2.5.
The scenarios for the safety assessment shall be supplemented with:		
• A systematic approach to the formulation of scenarios and a consistent account of these scenarios in the safety report with background material.	Yes	The method for identification of scenarios and the scenarios themselves are presented in Chapter 7. The method is based on the use of safety functions plus good knowledge of the evolution of the repository (FEPs).
• Include a main scenario that describes the most probable evolution of the repository.	Yes	All scenarios are described in Chapter 7, including a main scenario based on the reference evolution that is described in Chapter 6.
• Perform a better evaluation of different combinations of unfavourable conditions, FEPs.	Yes	Radionuclide transport and dose calculations are handled probabilistically, which satisfies the requirement on combinations of unfavourable conditions. Scenarios that can be combined are identified in Chapter 7, and the risk is summarized in Chapter 10.
An explanation shall be given in the safety report as to why the analysis is limited to 10,000 years after closure.	Yes	The analysis is extended to 100,000 years pos-closure.

Requirements	Handled	Comment SKB
The safety analysis report shall be supplemented with information regarding consequence and risk calculations, including a sensitivity and uncertainty analysis. The uncertainties in the parameters used shall be taken into consideration, above all in the model for water flow. The analysis shall consider the design and location of plugs, grouting of waste packages in BMA and type of backfill for the different repository parts. The calculation results shall be based on a main scenario (that takes into account the most probable changes) and be presented with uncertainty intervals.	Yes	Uncertainties in data have been taken into consideration and are included in the probabilistic analysis. The manner of closure of different repository parts has been taken into consideration. However, no credit has been taken in the calculations for grouting of waste packages in BMA. The results from the main scenario are presented in Chapter 9. The results are reported with an uncertainty interval between the 5th and 95th percentiles.
The assessment of concrete and bentonite barriers shall be supplemented with respect to their physical degradation processes and interactions between chemical and physical degradation processes.	Yes	Chemical degradation of concrete and bentonite has been studied on a timescale of 100,000 years /Cronstrand 2007/. Freezing of concrete and bentonite has been studied as a physical degradation process /Emborg et al. 2007/. The interaction between these types of degradation has not been studied in detail. Since the concrete has burst due to freezing, chemical degradation is judged to be irrelevant.
Explanation of the simplifications made in the calculation models NUCLFLOW and FARF31 so that it is clearly evident that the simplifications are reasonable.	Yes	The validity of the models is discussed in the Model Summary Report /SKB 2008/ and in the report on radionuclide transport calculations /Thomson et al. 2008a/.
The account of how documentation and quality assurance have been carried out in SSR 2001 shall be supplemented.	Yes	Project documentation describes how documentation and quality assurance have been carried out for SFR 1 SAR-08. See section 2.7.
When the safety report is supplemented, consideration shall be given to the principle that certain issues, such as gas evolution in a late phase, can never be dismissed simply by reference to previous safety assessments.	Yes	No references are made to previous safety analysis reports for the purpose of dismissing any issue.
Construct models that can describe the influence of complexation on the final repository's barrier functions.	Ongoing	The work of constructing models that describe the influence of complexing agents is being pursued in cooperation with the Department of Nuclear Chemistry at Chalmers. For this safety assessment, a cross-check has been made against Kd values used for bentonite and geosphere in SR-Can. Furthermore, uncertainty intervals have been identified and these are applied in the probabilistic radionuclide transport calculations, see Chapter 8.
SKI 2007-06-08 SKI 2004/220 DOCS #58694		
The safety assessment shall be updated to make it clear what requirements are made on barriers and barrier functions at different points in time, and how these requirements, together with the scenarios, comprise a basis for justifying the consequence analyses that are done.	Yes	Chapter 5 describes SFR 1's safety functions and associated safety performance indicators and criteria. These serve as a basis for the method of identifying scenarios, which is described in Chapter 7. Explicit requirements on the barriers have not been formulated. A safety evaluation of existing barriers is done in the safety assessment.

Requirements	Handled	Comment SKB
The safety assessment's consequence calculations shall be reported in terms of doses and risks. Sensitivity and uncertainty analyses shall be used to shed light on the influence of uncertainties, including variation in time and space of the most important parameters and uncertainties in radionuclide content.	Yes	Dose and risk results are reported in Chapters 9 and 10. Probabilistic calculations take into account uncertainties in input data. Several calculation cases can illustrate a scenario in order to shed light on uncertainties in time and space.
The following shall be explained in the account of the safety assessment's consequence calculations:		
• Influence of location and design of the plugs at closure of SFR (at least a qualitative explanation).	Yes/No.	The influence of the plugs on the flow through the repository is discussed in /Holmén 2007/. Alternative locations for the plugs that seal the rock vaults and silo are discussed in /Enviros 2004/. Since the plugs have little influence on the flow through the tunnels, alternative locations of plugs in the tunnels are not judged to affect the repository appreciably. The design of the plugs has not been further discussed.
• How combinations of unfavourable conditions and processes have been identified and examined in a systematic way.	Yes	Selection of scenarios and possible combinations of scenarios are discussed in Chapter 7.
• Influence of gradual changes in concrete and/or bentonite barriers that affect transport properties, for example.	Yes	Degradation of the engineered barriers is included in the main scenario. Furthermore, the importance of the barriers is demonstrated in a residual scenario. Based on these scenarios, the importance of gradually degraded barriers is assessed in Chapter 9.
• Description and estimation of factors that contribute to uncertainties in the groundwater flow.	Yes	Factors that contribute to the uncertainty in groundwater flow are discussed and parameter distributions are estimated in /Holmén 2005, Holmén 2007/. Uncertainties in the conductivity of the rock and the transmissivity of fracture zones are among the contributing factors.
• A study of how the redox conditions in the repository can change in the long term and the influence of such effects.	Yes/No	An estimation has been made of the redox conditions in the repository showing that it is not possible to rule out oxidizing conditions during the last time period, see Chapter 6. An account is given in Chapter 5 of which nuclides are affected by the redox conditions.
• A clarification of whether retardation in the geosphere is regarded as a safety function or not, and if so how this is reflected in the calculations.	Yes	The safety functions are described in Chapter 5. Sorption in the geosphere is not regarded as a safety function. However, sorption in the geosphere is included in the radionuclide transport calculations.
Scenarios with permafrost shall be examined if they cannot be ruled out on good grounds.	Yes	Scenarios with permafrost are described in Chapter 7.
Questions that have been handled in SKB's SAFE project (such as gas evolution in a late phase) by reference to previous safety assessments shall be integrated in the safety assessment and assessed once again in the report, with reference to any new information.	Yes	No references are made to previous safety analysis reports for the purpose of dismissing any issue.
SSI 2003-12-08 Dnr6222/3019/01		
SKB shall augment and strengthen the assessment of the repository's long-term protective capability and environmental impact within the following areas:		

Requirements	Handled	Comment SKB
• Importance of uncertainties in the inventory of significant radionuclides.	Yes	Uncertainties in the inventory are presented in SFR 1 SAR in the part for “Facility design and operation”. The importance of the uncertainties is believed to be covered adequately in the calculation cases presented in Chapter 9.
• The importance of long-term climate change.	Yes	The importance of permafrost, glaciation and a warmer climate (greenhouse variant) is described in the reference evolution and the dose results from the main scenario, Chapters 6 and 9.
• The importance of the anticipated gradual degradation of the barriers.	Yes	Degradation of the barriers is included in the main scenario. Furthermore, the importance of the barriers is demonstrated in a residual scenario. Based on these scenarios, the importance of gradually degraded barriers is assessed in Chapter 9.
• Presentation of uncertainty and sensitivity analyses of dose and risk with respect to groundwater flows through repository parts, redox conditions, sorption data and input data to the biosphere models.	Yes	Uncertainties in data have been taken into account and are included in the probabilistic approach in radionuclide transport and dose calculations.
• The repository’s protective capability and radiological consequences for times beyond 10,000 years after closure.	Yes	The analysis extends to 100,000 years post-closure.
• Documentation and quality assurance of calculation models for biosphere.	Yes	Documentation of calculation models for the biosphere is provided in the background report for dose calculations /Bergström et al. 2008/ and in /Avila and Pröhl 2008/. These reports have undergone traceable factual review and have thus been quality-assured.
Uncertainties and simplifications in the biosphere analysis:		
• The description of how the calculation models for the biosphere have been derived from the conceptual description of the biosphere.	Yes	Described particularly for carbon-14 in the background report for dose calculations /Bergström et al. 2008/ and the model report for carbon-14 /Avila and Pröhl 2008/.
• The importance of neglecting accumulation of radionuclides in sea and lake sediments via throughflow of contaminated groundwater from the repository.	Yes	The importance of accumulation of radionuclides is discussed in the background report for dose calculations /Bergström et al. 2008/.
• The account of possible processes in the transition between ecosystems and how they can affect the calculated radiological consequences, particularly in the transition between a lake and agricultural land.	Yes	The transition between different ecosystems is discussed in the background report for dose calculations /Bergström et al. 2008/, but is also mentioned in the main report, Chapter 9.
• The importance of not taking up the forest ecosystem in the consequence analysis.	Yes	The forest system is included in the dose calculations, Chapter 9.
SSI 2006-02-27 Dnr2006/6-257		
The importance of possible long-term climate changes, particularly permafrost, for long-term radiation protection in SFR 1.	Yes	The importance of permafrost and glaciation, but also a warmer climate (greenhouse variant), is described in the reference evolution and the main scenario, Chapters 6 and 9.
The importance of the expected degradation of the barriers in the silo, BMA and BTF for long-term radiation protection in SFR 1.	Yes	Degradation of the barriers is included in the main scenario. Furthermore, the importance of the barriers is demonstrated in a residual scenario. Based on these scenarios, the importance of gradually degraded barriers is assessed in Chapter 9.

Appendix C

Activity content of a given radionuclide in the repository over time

This appendix is referred to in Chapter 1. The nuclide inventory for 2040 AD (corresponding to waste from 50 years' operation of the nuclear power plants), dose coefficients and half-lives according to Table C-1. 1 have been used in the decay calculations and in determining the relative radiotoxicity of the nuclides in SFR. The nuclide inventory is taken from General Part 1 "Facility design and operation", Chapter 6 "Radioactive substances and waste in the facility".

Based on the relevant inventory, the activity content is calculated as a function of time from closure in 2040 AD and 100,000 years forward in time as follows:

$$A^i(t) = A_0^i \cdot e^{\frac{-\ln 2}{T½} \cdot t} \qquad (1)$$

where

$A_0^i =$ the activity of radionuclide *i* at 2040 AD

$A^i(t) =$ the activity of radionuclide *i* at time *t*

$t =$ the time (years) after closure

$T½ =$ the half-life (years) of radionuclide *i*

The fact that certain radionuclides form radioactive "daughters" is also taken into account in the decay calculations. The following decay chains are considered:

$Zr93 \rightarrow Nb93m$

$Cm243 \rightarrow Pu239$

$Pu241 \rightarrow Am241$

$U238 \rightarrow U234 \rightarrow Th230 \rightarrow Ra226 \rightarrow Pb210 \rightarrow Po210$

The activity of the daughters has been calculated using the computer program EcologoDecay where the following equation is used /Bateman 1908/:

$$A^k(t) = A_0^k e^{-\lambda_k t} + \sum_{l=1}^{k-1} \left\{ A_l^0 \left\{ \prod_{j=1}^{k-1} \lambda_j \right\} \left[\sum_{j=1}^{k} \frac{e^{-\lambda_j t}}{\prod_{\substack{n=1 \\ n \neq j}}^{k} \lambda_n - \lambda_j} \right] \right\} \qquad (2)$$

where

k = radionuclide number *k* in the sequence in the decay chain

λ = decay constant (y^{-1})

$A_0^k =$ the activity of radionuclide number *k* in the decay chain at time *t = 0*

A^k = the activity of radionuclide number *k* in the decay chain at time *t,* formed by parent decay

The activity values obtained in this way are then multiplied by the dose coefficients to obtain the radiotoxicity:

$$Radiotoxicity_{ing}^{i}(t) = DCC_{ing}^{i} \cdot A^{i}(t)$$

where

$DCC_{ing}^{i} =$ the dose coefficient on oral ingestion for radionuclide *i*

$A^{i}(t)$ = the activity of radionuclide *i* at time *t*

$Radiotoxicity_{ing}^{i}(t) =$ the radiotoxicity of radionuclide *i* at time *t*

In order to then obtain the relative radiotoxicity of a radionuclide, the radiotoxicity of the nuclide at any given time is divided by the total radiotoxicity of the whole repository at closure, 2040 AD. The value obtained here is the fraction of the original radiotoxicity.

The radiotoxicity of the excavated rock is calculated as follows:

It is assumed that radiometric equilibrium prevails in the excavated rock mass.

The natural uranium content of the rock is set at 4 ppm /SGU 2008/.

The volume of excavated rock mass in SFR is about 400,000 m^3.

The density of the rock is estimated at 2,780 kg/m^3.

Natural uranium contains 99.275% U-238.

The specific activity of U-238 is $1.25 \cdot 10^4$ Bq/g.

The quantity of uranium in the excavated rock mass is thereby:

$m = 4 \cdot 10^{-6} \cdot 400{,}000 \cdot 2{,}780 = 4{,}448$ kg.

The activity of U-238 in the excavated rock mass is then:

$A = 4{,}448 \cdot 10^3 \cdot 0.99275 \cdot 1.25 \cdot 10^4 = 5.52 \cdot 10^{10}$Bq

The following decay chain is considered and the activity of the two daughters has been calculated using the computer program EcologoDecay:

$$U238 \rightarrow U234 \rightarrow Th230 \rightarrow Ra226 \rightarrow Pb210 \rightarrow Po210$$

Since radiometric equilibrium prevails, the activity of the daughter nuclides is equal to the activity of U-238.

Radiotoxicity has subsequently been calculated using the nuclides' dose coefficients. The total radiotoxicity of the excavated rock mass is 137,000 Sv.

The relative radiotoxicity of the excavated rock mass is then obtained by dividing the total radiotoxicity of the excavated rock mass at any given time by the total calculated radiotoxicity of the whole repository at the time of closure, 2040 AD.

Table C-1. The nuclide inventory in 2040 AD and dose coefficients.

Nuclide	Total amount (Bq)	Dose coefficient Sv/Bq on ingestion /EUR 1996/	Half-life (y) /Firestone et al. 1996/
Ac-227	5.09E+01	1.10E–06	21.773
Ag-108m	1.15E+11	2.30E–09	418
Am-241	4.97E+11	2.00E–07	432
Am-242m	2.96E+08	1.90E–07	141
Am-243	1.10E+09	2.00E–07	7,370
Ba-133	3.13E+09	1.50E–09	10.54
Be-10	1.22E+06	1.10E–09	1,600,000
C-14 oorg	4.12E+12	5.80E–10	5,730
C-14 org	1.77E+12	5.80E–10	5,730
Cd-113m	3.49E+10	2.30E–08	14.1
Cl-36	1.36E+09	9.30E–10	301,000
Cm-243	2.90E+08	1.50E–07	29.1
Cm-244	1.01E+10	1.20E–07	18.1
Cm-245	1.05E+07	2.10E–07	8,500
Cm-246	2.79E+06	2.10E–07	4,730
Co-60	9.31E+13	3.40E–09	5.27
Cs-134	9.65E+11	1.90E–08	2.065
Cs-135	5.14E+09	2.00E–09	3,200,000
Cs-137	1.35E+14	1.30E–08	30
Eu-152	5.36E+09	1.40E–09	13.5
Eu-154	2.75E+12	2.00E–09	8.59
Eu-155	6.02E+11	3.20E–10	4.753
Fe-55	2.13E+13	3.30E–10	2.735
H-3	3.92E+10	1.80E–11	12.25
Ho-166m	8.93E+09	2.00E–09	1,200
I-129	1.01E+09	1.10E–07	15,700,000
Mo-93	3.70E+09	3.10E–09	4,000
Nb-93m	5.46E+11	1.20E–10	16.1
Nb-94	2.03E+10	1.70E–09	20,300
Ni-59	9.46E+12	6.30E–11	76,000
Ni-63	1.15E+15	1.50E–10	100.1
Np-237	1.58E+08	1.10E–07	2,140,000
Pa-231	1.05E+03	7.10E–07	32,760
Pb-210	0.00E+00	6.90E–07	22.3
Pd-107	3.18E+08	3.70E–11	6,500,000
Pm-147	1.87E+12	1.00E–08	2.623
Pu-238	4.86E+10	2.30E–07	87.7
Pu-239	1.13E+10	2.50E–07	24,100
Pu-240	2.25E+10	2.50E–07	6,560
Pu-241	8.19E+11	4.80E–09	14.4
Pu-242	1.05E+08	2.40E–07	373,000
Pu-244	2.45E+01	2.40E–07	80,000,000
Ra-226	0.00E+00	2.80E–07	1,600
Ru-106	1.57E+09	7.00E–09	1.02
Sb-125	2.29E+12	1.10E–09	2.759
Se-79	1.27E+09	2.90E–08	1,130,000
Sm-151	6.99E+11	9.80E–11	90
Sn-126	1.59E+08	4.70E–09	100,000
Sr-90	1.28E+13	2.80E–08	28.8
Tc-99	4.12E+11	6.40E–10	211,000
Th-229	1.05E+01	4.90E–07	7,340
Th-230	3.15E+03	2.10E–07	75,400
Th–232	3.51E–03	2.30E–07	13,200,000,000
U-232	7.46E+05	3.30E–07	68.9
U-233	7.01E+02	7.80E–08	159,300
U-234	3.51E+07	4.90E–08	246,000
U-235	4.66E+08	4.70E–08	70,000,000
U-236	1.40E+07	4.70E–08	23,000,000
U-238	1.47E+09	4.50E–08	4,500,000,000
Zr-93	2.28E+09	1.10E–09	1,530,000

Appendix D

Interaction matrices for the repository, the geosphere and the biosphere and description of the diagonal elements

This appendix belongs to Chapter 3 – "Identification, prioritization and handling of FEPs". The following tables and interaction matrices are included:

Title	*From /ref./*
Table D-1. Definition of diagonal elements in the repository matrix	/SKB 2001b/
Table D-2. Definition of the diagonal elements in the geosphere matrix	/SKB 2001b/
Table D-3. Definition of the diagonal elements in the biosphere matrix	/SKB 2001b/
Table D-4. Definition of priorities used in the matrices	/SKB 2001b/
The repository matrix	/Gordon et al. 2008/
The geosphere matrix	/Gordon et al. 2008/
The biosphere matrix	/Gordon et al. 2008/

Table D-1. Definition of diagonal elements in the repository matrix /from SKB 2001b/.

Element name	Short description	Variables
1.1 Waste/cement	Waste and cement matrix of all waste types that are stabilised in cement, i.e. ion-exchange resin, sludge, scrap and trash allocated to the Silo, BMA and 1BTF.	Volume, dimensions, voids. Porosity, pore characteristics. Amount, characteristics of fractures. Amount, composition, surface characteristics of materials. Type, amount of chemicals. Type, amount of organic materials and components that can be utilised by microbes as nutrients and energy sources. Extent of cement hydration in cement/concrete components. Amount and composition of surface coating on steel packaging.
2.2 Waste/bitumen	Waste and bitumen matrix of all waste types that are stabilised in bitumen, i.e. ion-exchange resins and evaporator concentrates allocated to the Silo, BMA and BLA.	
3.3 Waste/non-solidified	All non-solidified waste in the different repository parts, i.e. ion-exchange resins in 1BTF and 2BTF, ashes in 1BTF, trash and scrap in BLA.	
4.4 Concrete packaging	Concrete packaging with reinforcement and expansion cassettes, when present, in concrete moulds in the Silo and BMA. Concrete packaging, reinforcement and rubber liners in concrete tanks in BTF. The two steel drums and the concrete in between the steel drums that are used as packaging for ashes in 1BTF.	
5.5 Steel packaging	All types of steel packaging that are used in the different repository parts, i.e. drums, boxes and containers, except the ash drums in 1BTF (included in element 4.4). .It also includes surface coating on the drums when present, e.g. paint.	
6.6 Concrete backfill	Concrete backfill surrounding the waste packages in the Silo and in BMA. Concrete that will be filled in the void between the concrete tanks and the vault walls in 2BTF, and the concrete that will be filled in between the drums in 1BTF.	
7.7 Concrete structures	Concrete structures in the different repository parts in terms of bottom, lid and outer as well as inner walls in the Silo and BMA and concrete floor in BTF and BLA. It also includes shotcrete and rock bolts in the rock walls in all repository parts.	
8.8 Bentonite barriers	Sand/bentonite in the bottom and top of the Silo and the bentonite surrounding the cylindrical concrete walls.	
9.9 Vaults and backfill	Voids and backfill in the Silo cupola, outside the concrete structures in BMA and outside the waste packages in 1BTF, 2BTF and BLA. It also includes the sand layer above the concrete lid and the gas release devices in the Silo.	

Element name	Short description	Variables
10.10 Water composition	Water composition, including colloids/ particles and dissolved gas, in waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Redox, pH, ionic strength, concentration of dissolved species, type and amount of colloids/ particles, amount and composition of dissolved gas, density and viscosity.
11.11 Hydrology	Water and water movement in waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Magnitude, direction and distribution of water flow, Degree of saturation, Amount of water, Water pressure, Aggregation state (water/ice).
12.12 Gas	Gas and gas movement in waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Amount, composition, volume, pressure, degree of saturation Magnitude, direction and distribution of gas flow.
13.13 Temperature	Temperature in waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Temperature.
14.14 Stress conditions	Stress and strain in waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Stress and strain, Swelling pressure in bentonite barriers.
15.15 Biological state	The biological state of waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Type, amount, mobility of microbes and bacteria (and other types of biomass).
16.16 Radionuclides and toxicants	Radionuclides and toxicants in solid, aqueous and gas phase in waste and barriers in the Silo, BMA, 1BTF, 2BTF and BLA.	Amount, type, chemical and physical form, concentration.
17.17 Tunnels (Boundary condition)	*The geometry of access tunnels and all physical components in tunnels, i.e. backfill, plugs and rock reinforcements (e.g. shotcrete, rock bolts etc). The definition also includes water and gas in the tunnels.*	*Those variables assigned to diagonal elements 5.5, 6.6, 7.7, 8.8, 10.10, 11.11, 12.12, 13.13, 14.14, 15.15 and 16.16 in the geosphere matrix (see Table D-2).*
18.18 Repository rock (Bound. cond.)	*Rock and fracture system in between as well as around the vaults and the Silo to a distance of about 20 to 30 m from the repository. The definition includes all solid phases as well as water and gas.*	

Table D-2. Definition of the diagonal elements in the geosphere matrix /from SKB 2001a/.

Element name	Short description	Variables
1.1 Silo (Boundary condition)	*The geometry of the Silo repository and the physical components in the Silo that via interactions can affect and be affected by properties and conditions in the physical components of the geosphere, i.e. bentonite barriers, sand/gravel, water and gas.*	*Those variables assigned to diagonal elements 7.7, 8.8, 10.10, 11.11, 12.12, 13.13, 14.14, 15.15 and 16.16 in the repository matrix (see Table D-1).*
2.2 BMA (Boundary condition	*The geometry of the BMA vault and the physical components in the BMA that via interactions can affect and be affected by properties and conditions in the physical components of the geosphere.*	
3.3 BTF (Boundary condition)	*The geometry of the BTF vaults and the physical components in 1BTF and 2 BTF that via interactions can affect and be affected by properties and conditions in the physical components of the geosphere.*	
4.4 BLA (Boundary condition)	*The geometry of the BLA vault and the physical components in the BLA that via interactions can affect and be affected by properties and conditions in the physical components of the geosphere.*	

Element name	Short description	Variables
5.5 Tunnel/bore holes/backfill	The physical components included in this diagonal element are the access tunnels with their backfill (crushed rock) and rock reinforce-ments (shotcrete and rock bolts) and investigation bore holes and ventilation shafts and backfill in these.	Geometry, dimensions, volume. Density, homogeneity. Voids, pore and fracture characteristics.
6.6 Plugs	Plugs at the entrance of the Silo and repository vaults and at the entrance of the access tunnels, made of concrete and bentonite	Amount, composition, mineralogy, surface characteristics.
7.7 Repository rock matrix	The matrix of the rock in between as well as around the vaults and the Silo to a distance of about 20 to 30 m from the repository. The matrix of the rock in the disturbed zone around vaults and tunnels is also included.	Type and amount of organic materials and components that can be utilised by microbes as nutrients and energy sources.
8.8 Repository rock fracture system	The fracture systems, including fracture coatings, in the rock in between as well as around the vaults and the Silo to a distance of about 20 to 30 m from the repository. The fractures in the disturbed zone around vaults and tunnels are also included.	Type and amount of naturally occurring radionuclides in rock minerals.
9.9 Rock	Rock matrix, fracture systems and coating materials on fracture surfaces in the rock outside the repository rock.	
10.10 Water composition	Water composition, including colloids/ particles and dissolved gas, in tunnels, plugs, and investigation boreholes and in rock matrix and fractures in all rock in the geosphere system.	Redox, pH, ionic strength, Concentration of dissolved species, Type and amount of colloids/particles, Amount and composition of dissolved gas, Density and viscosity.
11.11 Hydrology	Water in all physical components of the geosphere system and water movement in plugs, tunnels boreholes, and fracture systems in the rock.	Magnitude, direction and distribution of water flow, Degree of saturation, Amount of water, Water pressure, Aggregation state (water/ice).
12.12 Gas	Gas and movement of gas in tunnels, plugs, investigation boreholes and in the matrix and fractures in rock. Naturally occurring radionuclides in gaseous phase are also included here.	Amount, composition, volume, pressure, degree of saturation. Magnitude, direction and distribution of gas flow.
13.13 Temperature	Temperature in plugs, tunnels, investigation bore holes, rock and fracture systems.	Temperature.
14.14 Stress conditions	Stress and strain in tunnels, plugs, investigation bore holes, rock and fracture systems.	Stress and strain, Swelling pressure in bentonite.
15.15 Biological state	The biological state of plugs, tunnels, investigation bore holes, rock and fracture systems.	Type, amount, mobility of microbes and bacteria (and other types of biomass).
16.16 Radionuclides and toxicants	Radionuclides and toxicants, originating from the repository, in solid, aqueous and gas phase in plugs, tunnels, investigation boreholes, rock and fracture systems.	Amount, type, chemical and physical form, concentration.
17.17 Biosphere (Boundary condition)	*Physical and biological components in the biosphere that via interactions can affect and be affected by properties and conditions in the physical components of the geosphere.*	*Those variables assigned to diagonal elements 2.2 to 7.7 and 10.10 to 15.15 in the biosphere matrix (see Table D-3.).*
18.18 External rock (Boundary condition)	*Rock beneath and around the rock included in the geosphere system.*	*Variables that can affect water composition, hydrology, gas, temperature, stress conditions and biological state in the geosphere components.*

Table D-3. Definition of the diagonal elements in the biosphere matrix /from SKB 2001b/.

Element name	Short description	Variables
1.1 Geosphere (Boundary condition)	*The physical components in the geosphere that via interactions can affect and be affected by properties and conditions in the components of the biosphere, i.e. rock, backfill in tunnels and bore holes and ventilation shafts, plugs, water and gas.*	*Those variables assigned to diagonal elements 5.5, 6.6, 9.9, 10.10, 11.11, 12.12, 13.13, 14.14, 15.15 and 16.16 in the geosphere matrix (see Table D-2).*
2.2 Quaternary deposits	Loose deposits including recent materials (e.g. soil, fine grain sediments, large grain sediments and till) and surface rock (out crops). In addition, buildings and structures such as roads, road-banks, bridges and houses are included. Interface between rock or sediments and air, and rock or sediments and surface waters.	Amount, depth, location, spatial distribution, grain size distribution, pore- and fracture characteristics, composition, mineralogy, surface characteristics. Baseline topography, e.g. land and bottom contours.
3.3 Primary producers	Primary producers of organic matter (plants, algae, trees etc). Particles and solids deposited on surfaces of primary producers are also included.	Type and amount. Location and size. Number of humans living at different places. Behaviour, e.g. living habits, culture, technical development etc. Rate of growth and life time. Radiologic and toxic effects.
4.4 Decomposers	Bacteria, worms, snails, fungi etc that decomposes dead organic matter. The decomposers live usually in the Quaternary deposits. Particles and solids deposited on surfaces of the decomposers are also included.	
5.5 Filter feeders	Mussels, hydroids, sponges, insect larvae etc that filter water. Filter feeders are living on rock surfaces and on loose deposits in water.	
6.6 Herbivores	Plant eaters (e.g. snails, insects, cow, sheep etc) that live both on land and in water. Omnivores are included here and in 7.7, e.g. bear.	
7.7 Carnivores	Animal eaters (e.g. fish, eagle, seal, fox, birds etc) that live both on land and in water. Mosquitoes, parasites and tics are also included. Omnivores are included here and in 6.6, e.g. bear.	
8.8 Humans	All humans living in the affected area.	
9.9 None	*Comment: Originally topography that later was moved into 2.2.*	
10.10 Water in Quaternary deposits	The hydrology in Quaternary deposits in terms of the pore water flow characteristics in the unsaturated zone and the groundwater flow characteristics in the saturated zone. The physical state of the water is also included, i.e. water/frost/ice.	Level of groundwater table, water content, degree of saturation, water pressure, magnitude, direction and distribution of water flow, quantity of water in different physical states, i.e. water/frost/ice.
11.11 Surface water	All surface waters except water in Quaternary deposits, i.e. Öregrundsgrepen and other water recipients such as rivers, lakes etc. Rainwater on surface rock and ”droplets” sorbed on other surfaces, e.g. primary producers are also included as well as snow and ice on land.	Size, location, amount, pressure, wave lengths and velocities, water level, layering. Magnitude, direction, distribution of water flow. Amounts and movements of ice/snow on surfaces.
12.12 Water composition	Composition of water in Quaternary deposits and of surface waters. Includes particles in the water as well as the composition of snow and ice.	Redox, pH, salinity, Concentration of dissolved species, Type and amount and size of colloids/particles, Amount and composition of dissolved gas, Density and viscosity.
13.13 Gas/ Atmosphere	All gases in the biosphere including the atmosphere in terms of composition and movement. Composition includes the content of particulate (e.g. ice crystals, water droplets, pollen, etc).	Amount, pressure, movements, composition, particulate content and type, wind velocity, wind field,

Element name	Short description	Variables
14.14 Tempera-ture	Temperature in the physical components of the biosphere system.	Temperature
15.15 Radio-nuclides and toxicants	Radionuclides and toxicants in all physical and biological components of the system. 1) from the repository, 2) background levels (e.g. from Tjernobyl and the Forsmark Power plant.	Amount, type, chemical and physical form. Concentration Location
16.16 External conditions (Boundary condition)	*All external conditions that affect the local conditions that are considered in the biosphere matrix.*	*Human behaviour, wind conditions, Large scale weather systems, Large scale water movements and water composition*

Table D-4. Definition of priorities used in the matrices /from SKB 2001b/.

Priority No	Colour	Description
4	Pink	**Important interaction only in the water saturation phase – part of the Performance Assessment.** It can influence other parts of the process system included in this matrix, or other parts of the repository system not included in this matrix.
3	Red	**Important interaction – part of the Performance Assessment.** Could also influence other parts of the process system, (defined in this matrix), or other parts of the repository system. The interaction can be either a prerequisite for the PA or handled by assumptions or modelling efforts in the PA.
2	Yellow	**Interaction present – probably part of the Performance Assessment.** Limited or uncertain influence directly or via this interaction on other parts of the process system, or other parts of the repository system. However, this interaction can be in main focus in other matrices.
1	Green	**Interaction present – do not have to be considered in the Performance Assessment.** Negligible influence on other parts of the process system (defined in this matrix) and other parts of the repository system.
0	White	No identified interactions.

The repository matrix /from Gordon et al. 2008/.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	**Waste/ cement** a) Recrystallis.	NONE	NONE	Expans./contract.	Expans./contract.	NONE	NONE	NONE	NONE	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering	a) Water flow b) Capillary suct.	a) Corrosion b) Degrad.organic c) Gas flow	a) Cement hydration b) Heat conduction c) Exothermic reactions	Expans./contract.	Microbial activity	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering	NONE	NONE
2	NONE	**Waste/ bitumen**	NONE	NONE	Expans./contract.	NONE	NONE	NONE	NONE	a) Dissol./precip. b) Degrad.organic c) Diffusion d) Sorption e) Colloid filtering	a) Water flow b) Capillary suct.	a) Degrad.organic b) Gas flow	a) Heat conduction b) Exothermic reactions	Expans./contract.	Microbial activity	a) Dissol./precip. b) Degrad.organic c) Diffusion d) Sorption e) Colloid filtering	NONE	NONE
3	NONE	NONE	**Waste/non-solidified**	Expans./contract.	Expans./contract.	NONE	NONE	NONE	NONE	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering	a) Water flow b) Capillary suct.	a) Corrosion b) Degrad.organic c) Gas flow	a) Heat conduction b) Exothermic reactions	Expans./contract.	Microbial activity	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering	NONE	NONE
4	Expans./contract.	NONE	Expans./contract.	**Concrete packaging** a) Recrystallis.	NONE	Expans./contract.	NONE	NONE	Expans./contract.	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering g) Erosion	a) Water flow b) Capillary suct.	a) Corrosion b) Degrad.organic c) Gas flow	a) Cement hydration b) Heat conduction	Expans./contract.	Microbial activity	a) Diffusion b) Sorption c) Colloid filtering	NONE	NONE
5	Expans./contract.	Expans./contract.	Expans./contract.	NONE	**Steel packaging**	Expans./contract.	NONE	NONE	Expans./contract.	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering g) Erosion	a) Water flow b) Capillary suct.	a) Corrosion b) Degrad.organic c) Gas flow	Heat conduction	Expans./contract.	Microbial activity	a) Diffusion b) Sorption c) Colloid filtering	NONE	NONE
6	NONE	NONE	NONE	Expans./contract.	Expans./contract.	**Concrete backfill** a) Recrystallis.	Expans./contract.	NONE	Expans./contract.	a) Dissol./precip. b) Degrad.organic c) Diffusion d) Sorption e) Colloid filtering f) Erosion	a) Water flow b) Capillary suct.	a) Degrad.organic b) Gas flow	a) Cement hydration b) Heat conduction	Expans./contract.	Microbial activity	a) Diffusion b) Sorption c) Colloid filtering	NONE	NONE
7	NONE	NONE	NONE	NONE	NONE	Expans./contract.	**Concrete structures** a) Recrystallis.	a) Expans/ contraction b) Bentonite expansion	Expans./contract.	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid filtering g) Erosion	a) Water flow b) Capillary suct.	a) Corrosion b) Degrad.organic c) Gas flow	a) Cement hydration b) Heat conduction	Expans./contract.	Microbial activity	a) Diffusion b) Sorption c) Colloid filtering	NONE	NONE
8	NONE	NONE	NONE	NONE	NONE	NONE	Bentonite expansion	**Bentonite barriers**	Bentonite expansion	a) Dissol./precip. b) Degrad.organic c) Diffusion d) Sorpt/ion-exch. e) Colloid filtering f) Colloid formation	a) Water flow b) Capillary suct.	a) Degrad.organic b) Gas flow	a) Heat conduction b) Exothermic reactions	Expans./contract.	Microbial activity	a) Diffusion b) Sorption/ion-exch. c) Colloid filtering	NONE	a) Bent. expans. b) Erosion
9	NONE	NONE	NONE	Expans./contract.	Expans./contract.	Expans./contract.	Expans./contract.	a) Expans./ contraction b) Bentonite expansion	**Vaults and backfill**	a) Dissol./precip. b) Degrad.organic c) Diffusion d) Sorption e) Colloid filtering f) Erosion	a) Water flow b) Capillary suct.	a) Degrad.organic b) Gas flow	a) Heat conduction b) Exothermic reactions	Expans./contract.	Microbial activity	a) Diffusion b) Sorption c) Colloid filtering	NONE	NONE
10	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Water uptake	a) Dissol./precip. b) Degrad.organic c) Water uptake	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Water uptake	a) Dissol./precip. b) Corrosion c) Degrad.organic	a) Dissol./precip. b) Corrosion c) Degrad.organic	a) Dissol./precip. b) Degrad.organic	a) Dissol./precip. b) Corrosion c) Degrad.organic	a) Dissol./precip. b) Degrad.organic c) Ion-exchange d) Water uptake e) Expans/dispers f) Montmorillonite transformation	a) Dissol./precip. b) Degrad.organic	**Water composition** a) Colloid formation/stability	a) Water flow b) Convection c) Osmosis d) Phase changes	a) Gas dissol./ degassing b) Chem. react. c) Corrosion d) Degrad.organic	Heat transport	NONE	Microbial activity	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Diffusion e) Sorption f) Colloid trsp	Mass flow	Mass flow
11	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Water uptake	a) Dissol./precip. b) Degrad.organic d) Water uptake	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Water uptake e) Redistribution	a) Dissol./precip. b) Corrosion c) Degrad.organic e) Erosion	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Erosion	a) Dissol./precip. b) Degrad.organic c) Erosion	a) Dissol./precip. b) Corrosion c) Degrad.organic d) Erosion	a) Dissol./precip. b) Degrad.organic c) Ion-exchange d) Water uptake e) Erosion	a) Dissol./precip. b) Degrad.organic c) Erosion d) Redistribution (subsidence)	a) Advection and mixing b) Chem. equilibr. c) Erosion d) Conc./dilution	**Hydrology**	a) Saturation b) Diss./degass. c) Two phase flow d) Expansion/ contraction	Heat advection	Water pressure interaction	Advection	a) Advection b) Dispersion c) Gas dissol./ degassing	a) Mass flow b) Disch./rech and pressure c) Biomass flow d) Contamin.trsp	a) Mass flow b) Disch./rech and pressure c) Biomass flow d) Contamin.trsp
12	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	a) Gas dissolution /degassing b) Colloid trsp	a) Saturation b) Two phase flow	**Gas**	a) Heat advection b) Heat conduction	Gas pressure interaction	a) Micr. activity b) Advection-gas	a) Advection-gas b) Colloid trsp	Gas transport	Gas transport
13	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Expansion/ contraction	a) Kinetics and equlibria b) Prop. changes c) Diffusion	Phase changes	a) Exp./contract. b) Convection	**Temperature**	Thermal stress interaction	Microbial activity	a) Kinetics and equilibria b) Diffusion c) Soret effect	Heat transport	Heat transport
14	Cracking	Cracking	Redistribution	Cracking	Deformation	Cracking	a) Cracking b) Redistribution	Redistribution (subsidence)	Redistribution (subsidence)	NONE	Water pressure interaction	NONE	NONE	**Stress conditions**	NONE	NONE	Stress and strain changes	Stress and strain changes
15	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial activity	NONE	Microbial activity	Microbial activity	NONE	**Biological state**	a) Microbial trsp b) Methylation/ transformation	Biomass flow	Biomass flow
16	Irradiation	Irradiation	Irradiation	Irradiation	Irradiation	Irradiation	Irradiation	Irradiation	Irradiation	a) Radiolysis b) Radionuclide decay c) Degradation	NONE	a) Radiolysis b) Degradation	Heat from decay	NONE	Irradiation (mutation)	**Radionuclides and toxicants** a) Radionuclide decay	Contaminant transport	Contaminant transport
17	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	Mass flow	Rech./disch. and pressure	Gas transport	Heat transport	Stress and strain changes	Biomass flow	Contaminant transport	**Tunnels (B.C.)**	NONE
18	NONE	NONE	NONE	NONE	Rock fall out	NONE	Rock fallout	a) Bent. expans. b) Erosion c) Rock creep d) Rock fallout	a) Rock fallout b) Rock creep	Mass flow	Rech./disch. and pressure	Gas transport	Heat transport	Stress and strain changes	Biomass flow	Contaminant transport	NONE	**Repository rock (B.C.)**

The geosphere matrix /from Gordon et al. 2008/.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	**SILO (B.C.)**	NONE	NONE	NONE	NONE	NONE	NONE	Bentonite expansion	NONE	a) Mass flow b) Erosion	Disch/recharge and pressure	Gas transport	Heat transport	Stress and strain changes	Biomass flow	Contaminant transport	NONE	NONE
2	NONE	**BMA (B.C.)**	NONE	NONE	NONE	NONE	NONE	NONE	NONE	Mass flow	Disch/recharge and pressure	Gas transport	Heat transport	Stress and strain changes	Biomass flow	Contaminant transport	NONE	NONE
3	NONE	NONE	**BTF (B.C.)**	NONE	NONE	NONE	NONE	NONE	NONE	Mass flow	Disch/recharge and pressure	Gas transport	Heat transport	Stress and strain changes	Biomass flow	Contaminant transport	NONE	NONE
4	NONE	NONE	NONE	**BLA (B.C.)**	NONE	NONE	NONE	NONE	NONE	Mass flow	Disch/recharge and pressure	Gas transport	Heat transport	Stress and strain changes	Biomass flow	Contaminant transport	NONE	NONE
5	NONE	NONE	NONE	NONE	**Tunnel/ borehole/ backfill**	Bentonite expansion	NONE	Bentonite expansion	Bentonite expansion	a) Dissol./precip. b) Corrosion c) Diffusion d) Sorption e) Colloid filtering f) Erosion g) Degr. of organics	a) Water flow b) Capillary suct. c) Flow in boreholes	a) Gas flow b) Corrosion c) Microbial activity	Heat conduction	Stress and strain changes	Microbial activity	a) Sorption b) Diffusion	NONE	NONE
6	NONE	NONE	NONE	NONE	a) Redistribution b) Bentonite exp.	**Plugs** a) Recrystallis.	NONE	Bentonite expansion	NONE	a) Diss/prec. Concr. b) Diss/prec. Bent. c) Diffusion d) Sorption/ion-exch e) Corrosion f) Colloid filtering g) Colloid formation	a) Water flow b) Capillary suct.	a) Gas flow b) Corrosion c) Microbial activity	Heat conduction	a) Bentonite expansion b) Stress and strain changes	Microbial activity	a) Sorption b) Diffusion	NONE	NONE
7	NONE	NONE	NONE	NONE	NONE	NONE	**Repository rock - rock matrix**	NONE	NONE	a) Dissol./precip. b) Diffusion c) Sorption	Capillary suction	a) Microbial activity b) Radon gener.	Heat conduction	Deformation	Microbial activity	a) Matrix diffusion b) Sorption	NONE	NONE
8	Bentonite expansion	NONE	NONE	NONE	Bentonite expansion	Bentonite expansion	NONE	**Repository rock - fracture system**	NONE	a) Dissol./prec. b) Diffusion c) Sorption d) Colloid filtering e) Erosion	a) Water flow b) Capillary suct.	a) Gas flow b) Microbial activity c) Radon gener.	Heat conduction	Deformation	Microbial activity	a) Matrix diff. b) Sorption c) Diffusion	NONE	NONE
9	NONE	NONE	NONE	NONE	Bentonite expansion	NONE	NONE	NONE	**Rock - rock matrix and fracture systems**	a) Dissol./prec. b) Diffusion c) Sorption d) Colloid filtering e) Erosion	Water flow	a) Gas flow b) Microbial activity c) Radon gen.	Heat conduction	Deformation	Microbial activity	a) Matrix diff. b) Sorption c) Diffusion	Erosion/ weathering	NONE
10	Mass flow	Mass flow	Mass flow	Mass flow	a) Diss./precip. b) Corrosion c) Ionic strength effects	a) Diss./precip. b) Corrosion c) Ion-exchange d) Water uptake e) Expans/dispers	Dissolution/ precipitation	Dissolution/ precipitation	Dissolution/ precipitation	**Water composition** a) Colloid formation/stability	a) Convection b) Water flow c) Osmosis d) Phase changes	a) Gas dissol./ degassing b) Chemical reactions	Heat conduction	NONE	Microbial activity	a) Diffusion b) Sorption c) Prec./diss. d) Colloid trsp	Mass flow	Mass exchange
11	a) Mass flow b) Rech/disch and pressure c) Erosion d) Biomass flow e) Contamin.trsp	a) Mass flow b) Rech./disch and pressure c) Biomass flow d) Contamin.trsp	a) Mass flow b) Rech./disch and pressure c) Biomass flow d) Contamin.trsp	a) Mass flow b) Rech./disch and pressure c) Biomass flow d) Contamin.trsp	a) Diss./precip. b) Corrosion c) Redistribution	a) Diss./precip. b) Corrosion c) Erosion d) Water uptake	Diss./precip.	a) Diss./precip. b) Erosion	a) Diss./precip. b) Erosion	a) Advection and mixing b) Chemical equilibria c) Erosion d) Conc./dilution	**Hydrology**	a) Saturation b) Diss./degass. c) Two phase flow d) Expansion/ contraction	Heat advection	Water pressure interaction	Advection	a) Advection b) Dispersion c) Gas dissol./ degassing	a) Mass flow b) Disch./rech and pressure c) Biomass flow d) Contamin trsp	a) Mass exchange b) Disch./rech and pressure c) Biomass exch.
12	Gas transport	Gas transport	Gas transport	Gas transport	NONE	NONE	NONE	NONE	NONE	a) Gas dissol./ degassing b) Colloid trsp	a) Saturation b) Two phase flow	**Gas**	a) Heat adv. b) Heat cond.	Gas pressure interaction	a) Biological activity b) Advection-gas	a) Advection-gas b) Colloid trsp	Gas transport	Gas exchange
13	Heat transport	Heat transport	Heat transport	Heat transport	a) Kinetics and equilibria b) Expansion/ contraction	a) Kinetics and equilibria b) Expansion/ contraction	a) Kinetics and equilibria b) Expansion/ contraction	a) Kinetics and equilibria b) Expansion/ contraction	a) Kinetics and equilibria b) Expansion/ contraction	a) Kinetics and equilibria b) Property changes c) Diffusion	Phase changes	a) Expansion/ contraction b) Convection	**Temperature**	Thermal stress interaction	Microbial activity	a) Kinetics and equilibria b) Diffusion c) Soret effect	Heat transport	Heat exchange
14	a) Stress/strain changes b) Rock fallout c) Rock creep	a) Stress/strain changes b) Rock fallout c) Rock creep	a) Stress/strain changes b) Rock fallout c) Rock creep	a) Stress/strain changes b) Rock fallout c) Rock creep	a) Rock creep b) Stress redist. c) Rock fall out	a) Cracking b) Rock creep	Stress redistribution	Stress redistribution	Stress redistribution	NONE	Water pressure interaction	NONE	NONE	**Stress conditions**	NONE	NONE	Change in rock surface location	Stress and strain changes
15	Biomass flow	Biomass flow	Biomass flow	Biomass flow	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial growth	Microbial activity	NONE	Microbial activity	Microbial activity	NONE	**Biological state**	a) Microbial trsp b) Methylation/ transformation	Biomass exchange	Biomass exchange
16	Contaminant transport	Contaminant transport	Contaminant transport	Contaminant transport	Irradiation	Irradiation	Irradiation	a) Irradiation b) Precipitation	Irradiation	a) Radiolysis b) Radionuclide decay c) Degradation	NONE	a) Radiolysis b) Degradation	Heat from decay	NONE	Irradiation (mutation)	**Radionuclides and toxicants** a) Radionuclide decay	Contaminant transport	NONE
17	NONE	NONE	NONE	NONE	a) Root penetration b) Borehole penetration	Root penetration	NONE	NONE	a) Consolid. b) Root penetr. c) Erosion/ weath.	Mass flow	a) Rech./disch and wells b) Press. change	Gas transport	Heat transport	a) Mechan. load b) Ice load	a) Root penetr. b) Intrusion c) Biomass exchange	Contaminant transport	**Biosphere (B.C.)**	NONE
18	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	Mass exchange	Rech./disch and pressure	Gas exchange	Heat exchange	Stress and strain changes	Biomass exchange	NONE	NONE	**External rock (B.C.)**

The biosphere matrix /from Gordon et al. 2008/.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	**GEOSPHERE (B.C.)**	a)Erosion/weath. b)Change in rock surface location	NONE	NONE	NONE	NONE	NONE	a)Material supply b)Settlement		Discharge/ recharge	Discharge/ recharge	Mass flux	Gas transport	Heat transport	Contaminant transport	NONE
2	a) Mech. load b) Consolidation	**Quaternary deposits** a)Relocation	a)Settlement b)Deposition	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption c)Material supply		a) Water transport b) Dehydration	a)Water transport b)Wave formation	a)Resuspension b)Leaching c)Sorpt./desorpt.	a)Resuspension b)Non-biol decomp c)Wind field changes d)Air pressure	a)Radiation b)Heat transport c)Heat storage	a)Sorption/desorpt. b)Dissolution	Export
3	Root penetration a) Rock b) Tunnels c) Biological	Root growth	**Primary producers** a)Stimul/Inhib.	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib.	a)Stimul./Inhib. b)Food supply d)Material supply		Root uptake	a)Interception b)Retard./Accel. c)Uptake/Excret. d)Covering	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod c)Wind retard.	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export *detached outflow of plankton*
4	Potential intrusion	a)Decomposition b)Bioturbation	a)Stimul./Inhib.	**Decomposers** a)Stimul/Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply d)Material supply		Decomposition	a)Decomposition b)Retard./Accel. c)Uptake/Excret. d)Movement	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export
5	Potential intrusion	Bioturbation	a)Stimul/Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	**Filter feeders** a)Stimul/Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply d)Material supply		NONE	a)Water-pumping b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	NONE	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export *detachment spawn*
6	Potential intrusion	Bioturbation	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply	**Herbivores** a)Stimul/Inhib.	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply d)Resource		NONE	a)Movement b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export
7	Potential intrusion	Bioturbation	a)Stimul./Inhib.	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. c)Feeding	**Carnivores** a)Stimul/Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding d)Resource		NONE	a)Movement b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export *swimming running*
8	Borehole intrusion	Disturbance *(dredging, digging)*	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. b)Food supply c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. b)Food supply c)Feeding d)Dispersal/ Extermination e)Material use	**Humans** a)Stimul/Inhib.		a)Water extraction b)Artific.infiltr.	a)Movement b)Retard./Accel. c)Uptake/Excret. d)Covering	a)Excretion b)Filtering c)Pollution	a)Gas uptake/rel b)Part. trap/prod c)Pollution d)Wind retard/acc.	a)Radiation b)Exo/Endo react. c)Heat transp. d)Antropogen eff	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	a)Export of energy b)Emigration?
9									**NONE (former topography)**							
10	a) Rech./disch. b) Press. change c) Mass flux d) Erosion/weath.	a)Erosion b)Water content change	a) Settlement b) Water uptake	a) Settlement b) Water uptake	NONE	a) Settlement b) Water uptake	a) Settlement b) Water uptake	a) Settlement b) Water use		**Water in quarternary deposits**	Discharge (recharge)	a) Erosion b) Mixing c) Dens. effects	a)Evapo./Cond. b)Sublimation	a)Heat transp. b)Heat storage	Mixing	Export
11	a) Rech./disch. b) Press. change c) Mass flux d) Erosion/weath. e) Ice-load	Erosion *(icescoring)*	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water use		Recharge (discharge)	**Surface water**	a) Mixing b)Dens. effects	a)Evapo./Cond. b)Sublimation c)Erosion *(seaspray/snowdrift)*	a)Radiation b)Exo/Endo react. c)Heat transp. d)Heat storage e)Light reflection	Mixing	Export/import
12	a) Mass flux b)Erosion/weath.	a) Sedimentation b) Precip./dissol. c) Erosion/weath.	a)Settlement b)Stimul./Inhib. c)Light attenu.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.		Water transport	Water transport	**Water composition**	a)Spray/Snowdrift b)Dissol./Degas.	a)Exo/Endo react. b)Light absorb. c)Light reflect./scatt. d)Adiab. compr.	a) Sorpt./desorpt. b) Dissol./precip. c) Sedimentation	Export
13	Gas transport	a)Erosion b)Deposition c)Oxidation	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	NONE	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.		a)Water transport b)Evapo./cond. c)Sublimation	a)Water transport b)Evapo./Cond. c)Precipitation d)Wind stress e)Sublimation	a)Precipitation b)Deposition c)Evapo./Cond. d)Dissol./Degas.	**Gas** -------------- **Atmosphere**	a)Radiation b)Exo/Endo react. c)Heat transp. d)Heat storage e)Adiab.temp.change f)Phase changes	a)Mixing b)Sorpt./desorpt. c)Photochem. reactions	Export
14	a)Heat transport b)Erosion/weath.	a)Weathering b)Thermal expans/contr	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.		Phase transitions	a)Phase transitions b)Convection	a)Kinetics & chem equil. b)Property changes c)Mixing	a)Pressure change b)Phase transitions	**Temperature**	a)Kinetics & chem equil. b)Phase transitions	Export of heat
15	Contaminant transport	a) Surface dep./uptake b) Irradiation	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure		NONE	NONE	a) Radiolysis b) Stab. isotopes c) Chem. react.	Phase transition	Heat from decay	**Radionuclides and toxicants** a) Decay	Export
16	NONE	a) Import b) Land rise	a) Import b) Insolation	Import	Import	Import	Import	a)Import of energy b)Immigration		Import	a) Sea level changes b) Sea currents	Import	a)Import b)Photochem-reactions	a) Import of heat b) Insolation	External load of contaminants	**External conditions (B.C.)**