Technical Report

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Main Report
Volume I

Deep repository for spent nuclear fuel

SR 97 – Post-closure safety

November 1999

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SKB

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Foreword

During the past three years, SKB has carried out an assessment of the long-term safety of a deep repository for spent nuclear fuel. The results of the project are reported in Swedish as ”Djupförvar för använt kärnbränsle; SR 97 – Säkerheten efter förslutning”. This report is an English translation titled “Deep repository for spent nuclear fuel; SR 97 – Post-closure safety”. The Main Report in its complete form consists of two parts with accounts of premises, methodology, analyses, results and conclusions. In addition there is a detailed summary which contains, among other things, the entire conclusion chapter from the complete version.

The report is primarily written for experts, but parts of the text should be of interest to non-specialists as well.

Allan Hedin has been responsible for methodology and for coordination of the different parts of the project, has written the summary, and has acted as writing editor for the complete main report. Patrik Sellin has dealt with near-field subjects. Anders Ström and Jan-Olof Selroos have been in charge of geosphere-related matters, and Ulrik Kautsky has been responsible for the biosphere. Lena Morén has worked with the climate and intrusion scenarios, while Fredrik Lindström has carried out the radionuclide transport calculations.

Many other individuals inside and outside SKB have also contributed in various ways to the project. If any are to be given special mention, the difficult choice falls on Johan Andersson of Golder Grundteknik, who participated as an expert in both geosphere matters and safety assessment in general, and Harald Hökmark of Clay Technology, who has worked with mechanical questions in the geosphere.

SKB is responsible for all judgements and conclusions in the report.

Stockholm, November 1999

Tönis Papp
Director Safety and Science

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Purpose and premises

In preparation for coming site investigations for siting of a deep repository for spent nuclear fuel, the Swedish Government and nuclear regulatory authorities have requested an assessment of the repository's long-term safety with the following purpose: "…to demonstrate that the KBS-3 method has good prospects of being able to meet the safety and radiation protection requirements which SKI and SSI have specified in recent years."

SR 97 is the requested safety assessment. The purpose is to demonstrate by means of a systematically conducted analysis whether the risk of harmful effects in individuals in the vicinity of the repository complies with the acceptance criterion formulated by the Swedish regulatory authorities, i.e. that the risk may not exceed 10^{-6} per year. Geological data are taken from three sites in Sweden to shed light on different conditions in Swedish granitic bedrock. The repository is of the KBS-3 type, where the fuel is placed in isolating copper canisters with a high-strength cast iron insert. The canisters are surrounded by bentonite clay in individual deposition holes at a depth of 500 m in granitic bedrock.

The assessment applies to a closed repository for spent nuclear fuel and thus does not include either safety during operation or safety of the repository for long-lived low- and intermediate-level waste. These matters are dealt with in separate reports.

Methodology

The methodology in the assessment entails first describing the appearance of the repository when it has just been closed and then analyze how the system changes with time as a result of both internal processes in the repository and external forces. The future evolution of the repository system is analyzed in the form of five scenarios. The first is a base scenario where the repository is postulated to be built entirely according to specifications and where present-day conditions in the surroundings, including climate, are postulated to persist. The four other scenarios show how the evolution of the repository differs from that in the base scenario if the repository contains a few initially defective canisters, in the event of climate change, in the event of earthquakes, and in the event of future inadvertent human intrusion. Repository evolution is broken down into thermal, hydraulic, mechanical and chemical processes, and the ultimate purpose of the analyses is to evaluate the repository's capacity to isolate the waste in the canisters, and to retard any releases of radionuclides if canisters are damaged. The time horizon for the analyses is at most one million years, in accordance with preliminary regulations.

Base scenario

By means of model studies and calculations, the base scenario analyzes how the radiotoxicity of the fuel declines with time, the repository's thermal evolution as a result of the decay heat in the fuel, the hydraulic evolution in buffer and backfill when they become saturated with water, and the long-term groundwater flow in the geosphere on the three sites.

Mechanical stresses on the canister stemming from groundwater pressure and swelling pressure from the buffer are examined, along with the long-term mechanical stability of the geosphere. The chemical evolution of bedrock and buffer, as well as corrosion of the copper canister, are also analyzed.

The overall conclusion of the analyses in the base scenario is that the copper canister's isolating capacity is not threatened by either the mechanical or chemical stresses to which it is subjected. The safety margins are great even in a million-year perspective.

Canister defect scenario

The internal evolution in initially defective canisters and the possible resultant migration of radionuclides in buffer, geosphere and biosphere are analyzed in the canister defect scenario. The result is estimates of dose and risk that can be compared with the acceptance criterion for a deep repository.

The scenario first shows that criticality cannot be expected to occur in the repository.

Analyses of the hydromechanical evolution in a damaged canister when water enters show that even the damaged canister prevents the release of radionuclides for a very long time, since intruding water is consumed by corrosion of the cast iron insert.

Dissolution of the fuel and solubility conditions for radionuclides released from the fuel are studied in analyses of the chemical evolution in a damaged canister. Model calculations show that hydrogen gas generated by corrosion of the cast iron insert contributes towards keeping the rate of fuel dissolution low.

Groundwater flow is studied on a local scale on the three sites. The analyses show that variation in results stemming from the natural variability in the rock often overshadows the variation caused by both differences between model concepts and uncertainties in boundary conditions, fracture structure, etc.

Radionuclide flux in the biosphere is modelled for a number of ecosystems, e.g. well and peatland. Peatland gives relatively high doses as a consequence of accumulation of e.g. Ra-226.

Data from the above-mentioned studies are then used for calculations of radionuclide transport in canister, buffer, backfill and geosphere. Releases from the geosphere are converted to doses in different ecosystems. Both reasonable and pessimistic values are estimated for all input data to the calculations, and in a few cases statistical distributions as well.

With reasonable data, the doses on all sites lie far below the dose limits that can be derived from the official acceptance criteria. The influence of uncertainties in data is analyzed by systematically substituting reasonable data for pessimistic data and studying the calculation result. The variation in flow-related data in the geosphere has the greatest impact on the result, followed by data uncertainties for the biosphere. Other conclusions are that our understanding of fuel dissolution needs to be improved, and that the probability and size of initial canister defects that escape quality-control inspection is difficult to estimate.

In order to obtain a risk measure that can be directly compared with the acceptance criterion, risk analyses in the form of simplified probabilistic calculations are also performed. The risk analyses show that all sites lie well below the acceptance criterion.

The maximum risk for release to a well is never more than 0.5 percent of the acceptance criterion, even when the calculations are extended a million years into the future. The same applies to releases to peatland for times up to 100,000 years, while the maximum risk here grows to about one-tenth of the acceptance criterion at the least favourable site at times after 100,000 years.

Climate scenario

The consequences of future climate change are explored in the climate scenario. Today's climate is relatively warm by historical standards, and future changes are expected for the most part to lead to a colder climate as a consequence of cyclical variations in insolation. A conceivable sequence of events, including severe glaciation, on each of the three sites is sketched for the coming 150,000 years.

The repository system's thermal, hydraulic, mechanical and chemical evolution under the changed conditions in the surroundings is studied in the form of a comparison with the evolution in the base scenario.

In the climate scenario as well, the overall conclusion is that the isolating capacity of the copper canister is not threatened by either mechanical or chemical stresses. The mechanical stresses are larger than in the base scenario, mainly due to higher rock and groundwater pressures in connection with a glaciation. The chemical stresses are roughly the same, partly because oxygen-containing groundwater is not expected to reach the canister. The strength calculations for the canister may need to be refined with more realistic, inhomogeneous material properties, and buffer erosion with extremely ion-poor groundwater compositions may require further study.

As far as the retarding capacity of the repository is concerned, for example in the event of initial canister damage, the most important changes take place in the biosphere. The repository sites are expected to be covered by ice sheets or sea during long periods, and the aggregate effect of climate change will therefore be a reduction of the dose consequences compared with a situation where the present-day climate persists.

Earthquake scenario

In the earthquake scenario, the consequences of earthquakes are analyzed by means of model studies where site-specific data are used for the structure of the geosphere and for earthquake statistics. The analysis method is new and includes several highly pessimistic simplifications. The analyses show that the probability of canister damage is comparable with the probability assumed for initial damage in the canister defect scenario. In the evaluation of the analysis method, it is shown how less pessimistic assumptions should lead to no canister damage at all in the model studies. The method will be refined.

Intrusion scenario

The scenario that deals with future inadvertent human actions that could conceivably affect the repository is surrounded by great uncertainties, chiefly because the evolution of human society is in principle unpredictable. SR 97 discusses how conceivable societal evolutions and future human actions that affect the repository can nevertheless be categorized to some extent. In an illustrative example, a situation is analyzed where a canister in the repository is inadvertently penetrated by rock drillers. Dose and risk are calculated for the drilling personnel and for a family that settles on the site at a later point in time. The risk to both drilling personnel and family is judged to lie well below the acceptance criterion, since the probability of the analyzed events is estimated to be very small.

Conclusions

The principal conclusion of the SR 97 safety assessment is that the prospects of building a safety deep repository for spent nuclear fuel in Swedish granitic bedrock are very good.

The three analyzed sites reflect reasonable variations of the conditions in granitic bedrock in Sweden. The analysis does not provide support for attaching any significant importance to differences in long-term safety between sites in a weighing together of all the factors that influence the siting of a deep repository.

Another conclusion is that the methodology that is used in SR 97 comprises a good foundation for future safety assessments that will be based on data from completed site investigations.

The results of the assessment also serve as a basis for formulating requirements and preferences regarding the bedrock in site investigations, for designing a programme for site investigations, for formulating functional requirements on the repository's barriers, and for prioritization of research.

The next stage in the siting of a deep repository entails investigation of the bedrock at a number of candidate sites in Sweden. It is SKB's judgement that the scope of the safety assessment and confidence in its results satisfy the requirements that should be made in preparation for such a stage.

1 Purpose and premises

Under Swedish law, the owners of nuclear reactors are obligated to see to it that radioactive waste from their activities is managed and disposed of safely. The Swedish power utilities jointly own Svensk Kärnbränslehantering AB, SKB (the Swedish Nuclear Fuel and Waste Management Company), whose mission is to develop methods for managing radioactive waste and to build and operate the facilities required for this.

Spent nuclear fuel is an important component in the radioactive waste, since it is both highly radioactive (high-level) and long-lived. At present, spent fuel is stored for a year or so at the reactor, after which it is transferred to CLAB, a central interim storage facility for spent nuclear fuel. According to SKB's plans, after 30 to 40 years of interim storage the fuel will be encapsulated in copper canisters and disposed of at a depth of approximately 500 metres in the crystalline bedrock. The facilities required for this, an encapsulation plant and a deep repository, have not yet been sited and built.

The system will be constructed over a period of several decades. Siting of facilities and systems is done in collaboration with concerned municipalities and under the supervision of safety and radiation protection authorities, all subject to the approval of the Government.

1.1 Why SR 97?

In preparation for the next stages in the realization of the system, the Swedish Government stated the following in its decision following the review of SKB's research programme RD&D 95 /SKB, 1995a/:

"A safety assessment of the repository's long-term safety should, in the opinion of the Government, be completed before an application for a permit to construct an encapsulation plant is submitted, likewise before site investigations on two or more sites are commenced."

This report gives an account of the requested safety assessment before site investigations are commenced. The working title of the analysis is SR 97 (Safety Report 97).

In its review of SKB's RD&D 98 /SKB, 1998/, the Swedish Nuclear Power Inspectorate (SKI) clarifies its view of the purpose and requirements for SR 97 /SKI, 1999/:

"The purpose is to demonstrate that the KBS-3 method has good prospects of being able to meet the safety and radiation protection requirements which SKI and SSI have specified in recent years."

SKI also writes: "…that SR 97, besides demonstrating a methodology for safety assessment, should also serve as a basis for:

- demonstrating the feasibility of finding a site in Swedish bedrock which meets the requirements on long-term safety and radiation protection that are defined in SSI's and SKI's regulations,
- specifying the factors that serve as a basis for the selection of areas for site investigations,
- deriving which parameters need to be determined and which other requirements ought to be made on a site investigation,
- deriving preliminary functional requirements on the canister and the other barriers."

1.2 Purposes

Based on the above points, **four** concrete purposes for SR 97 can be formulated:

1. SR 97 shall serve as a basis for demonstrating the feasibility of finding a site in Swedish bedrock where the KBS-3 method for deep disposal of spent nuclear fuel meets the requirements on long-term safety and radiation protection that are defined in SSI's and SKI's regulations.

2. SR 97 shall demonstrate methodology for safety assessment.

The ambition of SR 97 is to carry out a complete analysis of the long-term safety of the KBS-3 system for deep disposal of spent nuclear fuel. The methodology employed in SR 97 includes:

- a systematic handling of all the internal processes and external conditions that can cause long-term changes in the repository, and
- a systematic handling of the different types of uncertainties that always surround the background data for an analysis.

SR 97 is based on data from three actual sites. Data have been taken from SKB's investigations at Gideå in Ångermanland, from Finnsjön in northern Uppland County and from the Hard Rock Laboratory on Äspö outside Oskarshamn in Småland. The sites have been selected as calculations examples to reflect different conditions in Swedish granitic bedrock as regards geology, groundwater flux, water chemistry, nearness to coast, northerly or southerly location, surrounding biosphere, etc.

The report on the execution and results of the analysis therefore serves as a direct basis for assessing: a) the feasibility of finding a safe site for a KBS-3 repository in Swedish bedrock, and b) the methodology for a safety assessment.

3. SR 97 shall serve as a basis for specifying the factors that serve as a basis for the selection of areas for site investigations and deriving which parameters need to be determined and which other requirements ought to be made on a site investigation.

SR 97 comprises an important supporting document in the ongoing work of formulating requirements and preferences regarding the rock from the perspective of longterm safety. Results and experience from SR 97 are also used directly in the work of formulating an integrated programme for investigations and evaluations of sites. The conclusion chapter summarizes the way in which SR 97 comprises a background document for these two efforts.

4. SR 97 shall serve as a basis for deriving preliminary functional requirements on the canister and the other barriers.

How functional requirements can be derived from the results of the safety assessment is discussed in the conclusion chapter.

1.3 Delimitations

SR 97 is a complete safety assessment of the KBS-3 method for deep disposal of spent nuclear fuel, where geosphere data are taken from three actual sites in Sweden. The following fundamental premises also apply:

Post-closure safety

SR 97 deals with the long-term safety of the repository after closure. The construction and operating phases are not dealt with. These phases, as well as other aspects that pertain to the whole waste management system (encapsulation, transportation and deep disposal), are described in preliminary safety reports in conjunction with construction and operation. Together with SR 97, they comprise the background material for an integrated system analysis of all components in the waste management system to be published in 2000. Nor is SR 97 concerned with safety in connection with a prolonged open period or a partially closed repository.

Repository for spent nuclear fuel

SR 97 is concerned with a repository for spent nuclear fuel. Other long-lived waste will also have to be disposed of, for example core components from the decommissioning of nuclear power plants and waste from previous activities at the research reactor at Studsvik. This waste will be emplaced in a separate repository, which can be co-sited with the repository for spent nuclear fuel or with the final repository for radioactive operational waste, SFR, which is in operation today. The repository can also be sited separately.

A preliminary facility design and safety assessment for such a repository has been prepared in parallel with SR 97 and is presented in a separate report /SKB, 1999/. The safety-related consequences of a possible co-siting are not investigated in SR 97, but both assessments are based on the same geological data.

Holistic view of radiation protection

Long-term post-closure safety is one aspect of a holistic view of radiation protection in connection with waste management. A complete picture is presented in the system analysis mentioned above. The options allowed within the frames for KBS-3, as well as when and based on what information they will be evaluated and screened, are also discussed in that report.

1.4 Report structure

The structure of the account in SR 97 represents a development of the template devised in 1995 in safety report SR 95 /SKB, 1995b/.

The body of material for a safety assessment is very large. SR 97 is presented in the form of a main report to which three main references are closely associated, see Figure 1-1. In the main report and the three main references, reference is made to reports in SKB's report series or in the open literature.

The main report – ”Deep Repository for Spent Nuclear Fuel; SR 97 – Post-closure safety” – summarizes the entire safety assessment. It can be read separately from the others and includes methodology description, all essential results, as well as evaluations and conclusions. The report consists of two parts and a summary. All parts are available in Swedish and English.

“SR 97 – Waste, repository design and sites” describes in detail the waste, the repository design with canisters and buffer/backfill material, the three sites and the site-specific adaptations of the repository layouts that have been done. The report is available in both Swedish and English. Hereinafter, this report will be referred to as the “Repository System Report”.

“SR 97 – Processes in the repository evolution” describes the thermal, hydraulic, mechanical and chemical processes in fuel, canister, buffer and geosphere that control the evolution of the repository system. The report is available in both Swedish and English. Hereinafter, this report will be referred to as the “Process Report”.

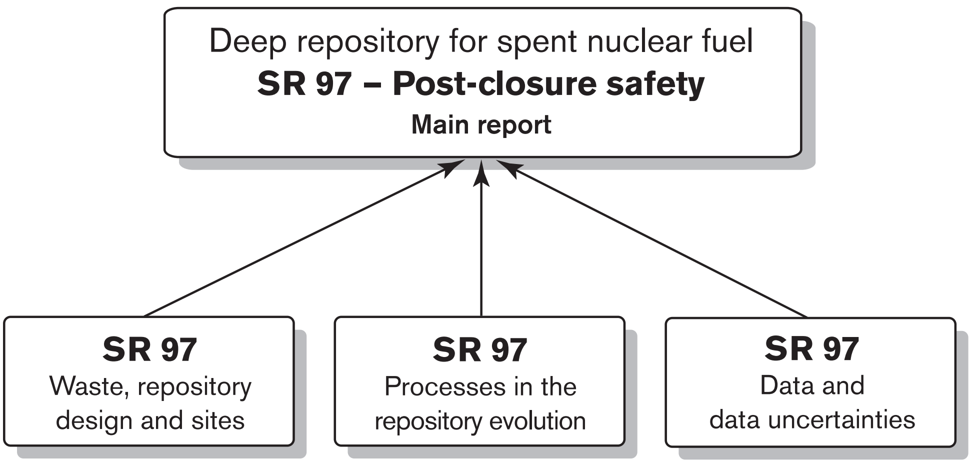

Figure 1-1. *Main report and some of the most important references to SR 97.*

"SR 97 – Data and data uncertainties" (in English only) contains a compilation of input data for calculations of radionuclide transport. There is also an evaluation of uncertainties in input data. Hereinafter, this report will be referred to as the "Data Report".

The outline of this main report is as follows: Following the introduction, which provides an overview of where in the programme SKB is and explains the purpose of the safety report, Chapter 2 provides a description of Swedish laws and regulations governing safety and radiation protection in nuclear waste management. Chapter 3 then explains the safety principles for the deep repository, while Chapter 4 presents the methodology for assessment of long-term safety.

Chapters 5 and 6 describe in brief the processes that are important in the evolution of the repository and the initial state of the repository at closure.

Chapter 7 describes and discusses the choice of scenarios, i.e. different conceivable evolutionary pathways for the repository, while Chapters 8–12 present the analyses of the different scenarios.

The report concludes with a chapter in which the results and experience from the work with SR 97 are discussed in relation to the purpose of the report and Swedish laws and regulations.

1.5 References

Miljödepartementet. Government Decision 11 of 1995-05-18.

SKB, 1995a. RD&D-Programme 95. Treatment and final disposal of nuclear waste. Programme for encapsulation, deep geological disposal, and research, development and demonstration.
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SKB, 1999. Deep repository for long-lived low- and intermediate-level waste – Preliminary Safety Assessment.
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SKI, 1999. SKI's evaluation of SKB's RD&D-Programme 98.
SKI Report 99:30 and 99:31. Statens kärnkraftinspektion.

2 Safety goals and acceptance criteria

The form and content of a safety assessment, and above all the criteria for judging the safety of the repository, are defined in regulations issued by the Swedish safety and radiation protection authorities. The regulations are based on framework legislation, the most important being the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act. Radiation protection matters are handled by a number of international bodies, and national legislation is often based on international rules and recommendations.

Long-term safety is regulated today by the Swedish Radiation Protection Institute's (SSI) "Regulations for final disposal of spent nuclear fuel" (SSI FS 1998:1). The regulations entered into force on 1 February, 1999.

In 1999, the Swedish Nuclear Power Inspectorate, SKI, distributed a draft version of "The Swedish Nuclear Power Inspectorate's regulations concerning safety in final disposal of nuclear waste".

2.1.1 SSI's regulations for final disposal of spent nuclear fuel

SSI writes that human health and the environment, now and in the future, shall be protected from the harmful effects of ionizing radiation. Nuclear activities must not cause more serious effects on human health and the environment outside Sweden's boundaries that what is acceptable within Sweden. A final repository shall be designed so that no additional measures are needed after closure to prevent or limit the escape of radioactive substances from the repository. Institutional controls and knowledge of the location of the repository in a distant future cannot be assumed. SSI's regulations apply to the long-term safety of a closed repository.

Protection of human health

The overall acceptance criterion for a deep repository is expressed in Section 5 of SSI's regulations:

"A final repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure is no more than 10^{-6} for a representative individual in a group that is exposed to the greatest risk."

The acceptance criterion is thus a risk measure. A risk calculation investigates what courses of events can lead to harmful effects, what their probability of occurring is, and the size of the injury (the consequence) for each course of events. The product of probability and consequence gives a sub-risk for each course of events. The aggregate risk is the sum of the sub-risks for different conceivable courses of events.

SSI stipulates an annual risk of 10^{-6} for individuals exposed to radiation from the repository. For a hypothetical situation with exposure that occurs with certainty (probability = 1), this corresponds to an annual radiation dose of 0.015 milliSieverts (mSv) from the repository. This can be compared with the natural background radiation, which is several mSv/y in Sweden.

The risk limit applies to a representative individual in the group that is exposed to the greatest risk. As an indication of the size of such a group, SSI mentions the population in an area where it is theoretically possible to site ten different deep repositories. Such an area is difficult to delimit in a risk calculation. As an alternative, SSI states that it "can be acceptable to carry out the calculations for an individual judged to be highly burdened, instead of an individual who is representative for the whole group's burden".

The risk limit for such an individual is set at 10^{-5}, which corresponds to a radiation dose of 0.15 mSv/y. The exposure models in SR 97 have not been adapted to the details of SSI's regulations, since the latter did not enter into force until towards the end of the assessment. However, the models are already designed in most cases to calculate doses to a small and highly exposed group which, for example, lives solely on contaminated food. The calculation result in SR 97 should therefore in most cases be compared with the risk criterion 10^{-5}/y, equivalent to a dose limit of 0.15 mSv/y for an exposure that occurs with certainty, see further section 9.10.4.

Environmental protection

SSI also states that:

"§6 Final disposal of spent nuclear fuel and nuclear waste shall be implemented so that biological diversity and sustainable utilization of biological resources are protected against the harmful effects of ionizing radiation."

"§7 An account shall be given of biological effects of ionizing radiation in affected habitats and ecosystems. The account shall be based on available knowledge of concerned ecosystems ..."

By "biological diversity" is meant diversity of species and genetic varieties among living organisms and the ecological complexes they comprise. Of special interest, says SSI, are organisms that are genetically unique or potentially important for the ecological processes, the biodiversity and the biological resources. The biological resources may be species or populations that have a market value, e.g. for cultivation or as a food source.

In the absence of established methodology, SSI says that the precautionary principle shall apply, i.e. the very suspicion of harmful effects on the environment shall be sufficient to intervene or refrain from a given activity.

In SR 97, the biological effects of a release are judged by comparison with the natural background radiation. If the releases are small compared with the background radiation, the effects should be negligible.

Intrusion

SSI stipulates that an account shall be given of the consequences of an inadvertent intrusion or other disturbance in the final repository or its vicinity. What is essential is not to describe the chain of events leading up to the intrusion, but to shed light on the repository's protective function after an intrusion. The protective capacity of a final repository must not be impaired by planned measures to hinder intrusion or facilitate retrievability.

Doses higher than 1 mSv/y, which could conceivably be encountered in connection with an intrusion into the final repository, will be assessed separately by SSI.

Time periods

SSI states that harmful effects in the future should not be regarded as less important than the harmful effects to which man or the environment are exposed today.

SSI emphasizes that the first 1,000 years after repository closure is the most important period to investigate, since the radiotoxicity of the waste is greatest then. The highest demands are made on the safety account for this period. The regulations also require an account of a case based on the assumption that the biosphere conditions prevailing at the time of the licence application do not change. The term "prevailing conditions" also takes into account known changes such as postglacial land uplift.

The period after the initial 1,000 years shall also be investigated, and SSI emphasizes the importance of accounting for the different types of uncertainties in the underlying data on which the analyses of different epochs are based.

Optimization

"§4 In conjunction with final disposal of spent nuclear fuel and nuclear waste, optimization shall be practised and account shall be taken of the best possible technology."

By "optimization" is meant limitation of radiation doses to man as far as is reasonably possible, taking into account both economic and societal factors. By "Best possible technology" is meant tried-and-tested technology in keeping with accepted scientific principles and taking into account both the benefit and cost of the measures.

As a comparison measure for optimization, SSI requires that the annual global collective dose as a result of expected releases during the first 1,000 years after closure be calculated and summed over 10,000 years. SSI stipulates no requirements on limitation of the collective dose.

The KBS-3 design, which serves as the basis for the repository system whose long-term safety is being assessed, has been developed over the past two decades. Large-scale and long-term tests are under way in order to permit a future optimization of the system. SR 97 is based on present-day technology and available data from the three sites. Since the purpose has not been to build a repository on any of the three sites, no site-specific optimization has been done. Background data and planning for such an optimization will be presented in the system analysis that is to be completed by 2000.

2.1.2 SKI's draft version of regulations concerning safety in final disposal of nuclear waste

The regulations from SKI are as yet only available in a draft version. Among other things, the regulations talk about how the safety assessment should deal with various internal and external conditions that may have a bearing on safety. SKI emphasizes the importance of a systematic handling of uncertainties, and that the models and data used should be demonstrated to be applicable as far as possible. The assessment must cover the first million years after repository closure.

Since the regulations are not yet available in a final version, it has not been possible to use them as a direct basis for SR 97. In general, it can nonetheless be said that all aspects dealt with in the draft version are also covered in one way or another in SR 97.

3 The KBS-3 system, safety principles

As the work of developing a safe deep repository in Sweden has proceeded, a philosophy has emerged regarding how the radioactive waste in Sweden is to be managed. In brief, it entails the following:

- Long-term safety shall not require future monitoring and maintenance.
- The repository shall be designed to permit possible future measures to modify the repository or retrieve the waste.
- The long-term safety of the repository shall be based on multiple engineered and natural barriers which contribute via different functions to the repository's total safety.

The practical application of this philosophy has resulted in a repository design with a multiple barrier system, the KBS-3 system.

This chapter provides a brief description of the KBS-3 system and the safety principles that have served as a basis for the design of the system. The description is needed as a general introduction to the safety assessment and as background to the method description in Chapter 4. A considerably more detailed description of the repository system, appropriate to the needs of the safety assessment, is provided in Chapters 5 and 6.

3.1 Safety principles for a deep repository

The KBS-3 repository for spent nuclear fuel is designed primarily to isolate the waste. If the isolation function should for any reason fail in any respect, a secondary purpose of the repository is to retard the release of radionuclides. This safety is achieved with a system of barriers, see Figure 3-1:

- The fuel is placed in corrosion-resistant copper canisters. Inside the five-metre-long canisters is a cast iron insert that provides the necessary mechanical strength.
- The canisters are surrounded by a layer of bentonite clay that protects the canister mechanically in the event of small rock movements and prevents groundwater and corrosive substances from reaching the canister. The clay also effectively adsorbs many radionuclides that could be released if the canisters should be damaged.
- The canisters with surrounding bentonite clay are emplaced at a depth of about 500 metres in the crystalline bedrock, where mechanical and chemical conditions are stable in a long-term perspective.
- If any canister should be damaged, the chemical properties of the fuel and the radioactive materials, for example their poor solubility in water, put severe limitations on the transport of radionuclides from the repository to the ground surface. This is particularly true of those elements with the highest long-term radiotoxicity, such as americium and plutonium.

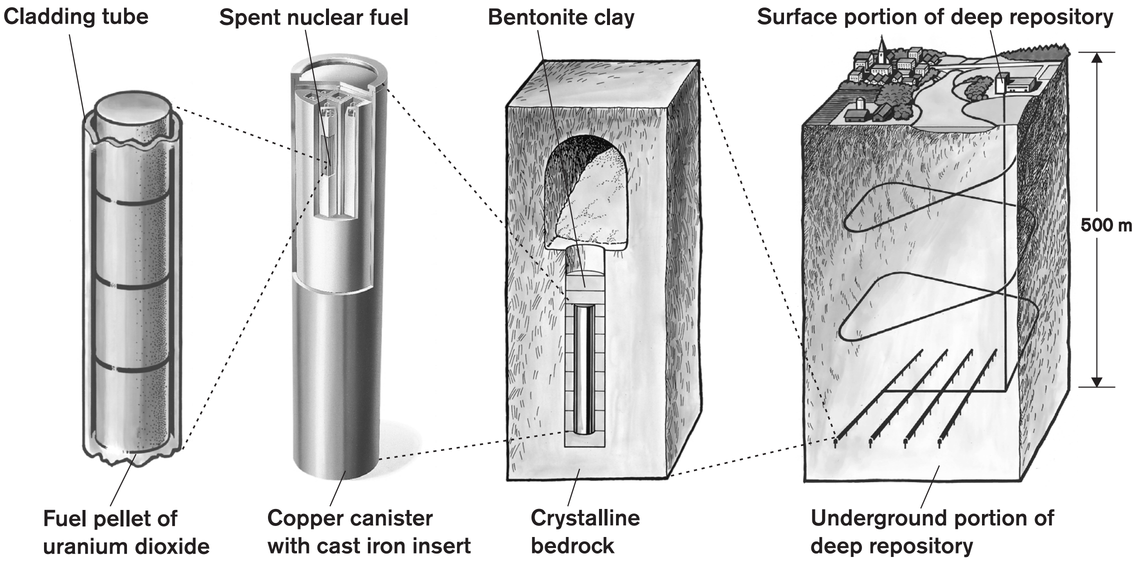

Figure 3-1. *The KBS-3 system.*

The repository is thus built up of several barriers which support and complement each other. The safety of the repository must be adequate even if one barrier should be defective or fail to perform as intended. This is the essence of the multiple barrier principle.

Another principle is to make the repository "nature-like", i.e. to use natural materials such as copper for the outer shell of the canister and bentonite clay for the buffer. Choosing materials from nature makes it possible to judge and evaluate the materials' long-term stability and behaviour in a deep repository based on knowledge of natural deposits. For the same reason, the repository should cause as little disturbance of the natural conditions in the rock as possible. Above all, an attempt is made to limit the chemical impact of the repository in the rock.

3.2 Isolation – the primary function of the repository

The primary function of the deep repository is to isolate the waste from man and the environment. This is achieved directly by the copper canister. The buffer contributes indirectly to the isolation function by keeping the canister in place and preventing corrosive substances from reaching the canister.

The rock also contributes to isolation of the waste by offering a stable chemical and mechanical environment for the canisters and the buffer. Chemical conditions are determined primarily by the composition of the groundwater. The composition is favourable, since the water contains only low concentrations of substances that could be harmful to the copper canister only and the bentonite. It is also desirable that the water should flow slowly past the repository so that the influx of undesirable substances is limited. Mechanically, the Swedish crystalline bedrock offers a long-term stable environment for a deep repository.

Even though the copper canister is responsible for direct isolation of the waste, the other parts of the repository are necessary for this isolation to work. Isolation is thus ensured not only by the canisters, but by the fact that all the components work together in a system.

3.3 Retardation – the secondary function of the repository

If the isolating function should for some reason be compromised, or if any canister should have an initial defect not detected by post-fabrication inspection, the repository has a secondary retarding function. By this is meant that the time it takes for radionuclides to be transported from the repository to the biosphere is long enough so that their radiotoxicity declines considerably before the radionuclides reach man or the human environment.

All barriers contribute to the retarding function of the repository. Even a partially damaged copper canister can effectively contribute to retardation by impeding the influx of water into the canister and the transport of released radionuclides out of it. The fuel, in which the majority of the radionuclides lie embedded, consists of a durable ceramic material which makes a significant contribution to retardation.

If the fuel comes into contact with groundwater, a very slow dissolution process starts which leads to the release of radionuclides. Here, an important property of many of the most long-term radiotoxic radionuclides enters into the picture: they are poorly soluble in water, the medium in which radionuclides might conceivably be transported through both the pores of the buffer and the fracture system in the rock. Many of the radionuclides with the highest long-term toxicity tend to be retained in the clay buffer by adherence to the surfaces of the clay particles. The rock contributes in several ways to this retardation; it may take thousands of years or more for radionuclides dissolved in the groundwater to travel through rock fractures from the repository at a depth of 500 metres up to the ground surface. Because the radionuclides penetrate into microfissures containing stationary water and in many cases adhere to their surfaces, they have a much longer travel time than the groundwater itself.

3.4 Dilution and dispersal

Dilution and dispersal have also occasionally been mentioned as a third safety function: By locating the repository so that any releases are highly diluted in the biosphere, the consequences are mitigated. This effect is not regarded as a safety function in SR 97, for several reasons:

- The biosphere, where dilution takes place, changes much faster than the repository system, and in a way that is difficult to predict. It is therefore not reasonable to base a long-term safety function on conditions in the biosphere.
- Although the consequences for those most affected by a release are mitigated, a larger population may be affected.

Dilution is nevertheless an important factor that influences radionuclide migration in the biosphere and thereby the consequences of a release from the repository. An evaluation of the dilution conditions at a repository site must therefore be included in a safety assessment, but dilution is not regarded as a safety function in itself.

3.5 How long should the repository function?

The repository should function as long as the waste is hazardous. It takes many millions of years for all radioactive materials to decay to stable substances. By then, however, their radiotoxicity has long since declined to levels comparable to the radiotoxicity of the uranium ore originally mined to produce the fuel.

Approximately eight tonnes of natural uranium are enriched to fabricate one tonne of fuel for a Swedish reactor. During operation, the radiotoxicity of the fuel increases as new radioactive substances are formed when uranium nuclei undergo fission. Figure 3-2 shows how the radiotoxicity of the spent fuel subsequently declines with time. After approximately 100,000 years, the radiotoxicity of a tonne of spent fuel is on a par with that of the eight tonnes of natural uranium used in fabricating the fuel.

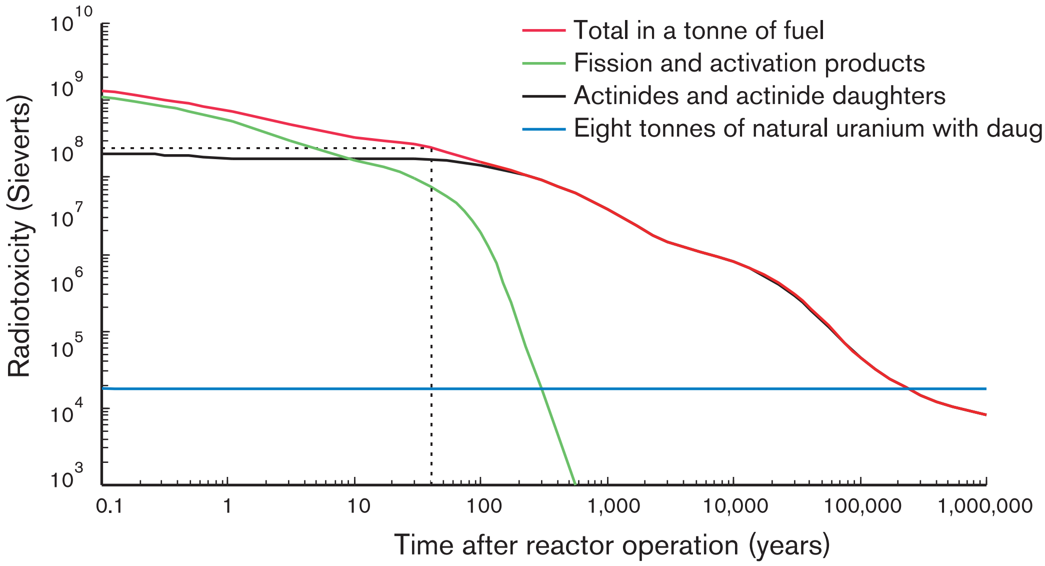

Figure 3-2. *Toxicity of the waste as a function of time for Swedish BWR fuel with a burnup of 38 MWd/t U. Radiotoxicity pertains to ingestion via food. After 30 to 40 years of interim storage, the fuel will be deposited in the final repository. Reworked from Hedin /1997/.*

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The figure 100,000 years can therefore be used as a guideline for how long the repository has to "function". However, this figure is not an absolute time limit in the evaluation of the repository's safety:

- On the one hand, radiotoxicity declines steadily and has e.g. after a thousand years fallen to about one-tenth of the level at deposition, about 40 years after operation. This is important in the evaluation of the repository's safety: With time, uncertainty regarding conditions in and around the repository grows, but at the same time the radiotoxicity of the fuel diminishes.
- On the other hand, even after 100,000 years there are both small quantities of radionuclides that can move relatively easily through the repository's barriers if the copper canister should be damaged, and large quantities of low-mobility nuclides.

The safety of the repository thus needs to be evaluated far into the future and constantly in the light of how radiotoxicity declines with time.

3.6 References

Hedin A, 1997. Spent nuclear fuel – how dangerous is it?
A report from the project "Description of risk".
SKB TR 97-13. Svensk Kärnbränslehantering AB.

4 Methodology

There is no standardized method for carrying out a safety assessment of a deep repository for spent nuclear fuel. Different methods and variants are employed by different organizations the world over. Differences in approach depend in part on different national conditions and in part on a general methodology development. Nevertheless, many common features can be distinguished in safety assessments that have been conducted during the past decade, albeit under somewhat varying guises. This is evident, for example, from a review conducted under the auspices of the OECD/NEA /NEA, 1997a/, where a recommendation is also given of what a safety report should contain. All of these elements are included in SR 97, most in this Main Report, a few only in background reports.

This chapter describes the methodology used in carrying out SR 97. A systems perspective has been adopted throughout in the execution and reporting of the assessment. Another distinguishing feature is the attempt to strike a balance between different aspects of repository evolution. In previous assessments there has often been a very heavy emphasis on radionuclide transport. In SR 97 the most fundamental function, isolation, is more to the fore than before.

4.1 What is a safety assessment?

4.1.1 Systems perspective

As stated in Chapter 3, the safety of the repository is built up around isolation and retardation. As a point of departure for a discussion of how a safety assessment can be carried out, we pose the question: What could threaten isolation?

The copper canisters will be acted on chemically by corrosion, albeit very slowly. The groundwater contains low concentrations of sulphide which react with copper. The corrosion rate is determined by the sulphide concentration and how rapidly sulphide reaches the canister. This is in turn determined by how much sulphide-containing groundwater reaches the repository at any given instant, and by how rapidly sulphide is transported through the buffer and up to the canister.

The canisters will also be acted on mechanically: The buffer swells when it comes into contact with the groundwater and gradually builds up a considerable swelling pressure against the canister. Large rock movements could also act mechanically on the canister.

The process of radioactive decay in the fuel evolves heat which leads to a temperature rise in canister, buffer and rock. If the buffer becomes too hot, it will be altered chemically, which will have consequences for both how sulphide is transported through the buffer and the buffer's swelling capacity.

The examples show that we are faced with analyzing the evolution of a system of coupled thermal, hydraulic, mechanical and chemical processes.

The point of departure for the assessment is the conditions which prevail when the repository has just been built and closed. The original thickness of the copper shell is, for example, an obvious point of departure for studying the isolating capacity of the repository.

The changes in the repository are driven by both internal processes in the repository and external forces. The thermal evolution resulting from radioactive decay in the fuel and the corrosion of the surface of the copper shell are examples of internal processes. Climate changes (e.g. an ice age) or an earthquake are two types of external events which could affect the repository. A safety assessment deals primarily with the evolution of the repository itself, which is described in greater detail than that of the surroundings.

The safety assessment can therefore be said to consist of the following tasks:

- carefully describe the appearance or state of the repository system when it has just been built and closed,
- describe what changes the repository could conceivably undergo in time as a consequence of both internal processes and external forces,
- evaluate the consequences of the changes for safety.

The approach is general in the assessment of systems that change with time: A system is delimited by a system boundary and an initial state is described. The evolution of the system is thereafter determined by time-dependent internal processes and by interaction with the changing surroundings, Figure 4-1.

4.1.2 Safety criteria and confidence

The third point above, evaluation of the consequences for safety, leads to the question: Against which criteria should safety be assessed?

It is simple to formulate a general safety criterion for isolation: The copper shell must be intact, otherwise isolation is not complete.

Several factors and processes in the repository determine together whether isolation is upheld. It is therefore seldom meaningful to set up absolute safety criteria for the individual factors, since it is the combined effect that determines the consequences. Nevertheless, such factors as water flows or sulphide concentrations from the above example can be used as indicators of whether the circumstances are more or less favourable for isolation.

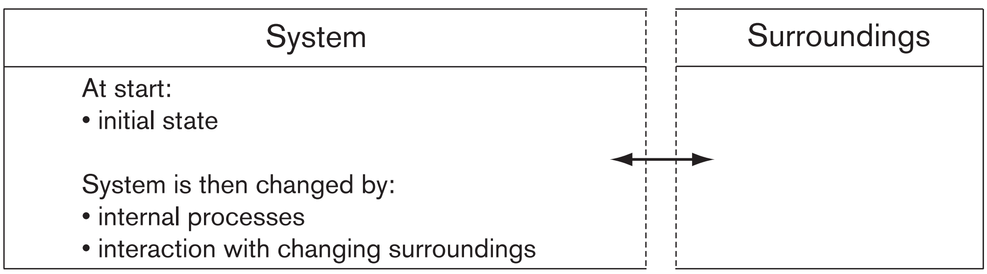

Figure 4-1. *Long-term changes are caused by internal processes in the repository and by external influences.*

The same can be said with regard to criteria for retardation: If the isolation of the waste has been breached, the ultimate consequence of insufficient retardation may be radiation damage to man and the environment. Absolute requirements exist for consequence assessment here in the form of official risk levels and dose limits. The scope of retardation is determined by numerous interacting factors in fuel, canister, buffer, rock and biosphere. It is therefore not meaningful to set up absolute criteria for the individual factors here either.

The formulation of safety criteria is elaborated on further in section 5.7 after the repository system has been described in greater detail.

Just as important as the assessment of the repository's isolating capacity and the numerical result of the analysis of radionuclide retardation is confidence in the results. The data underlying a safety assessment are always associated with deficiencies of various kinds. It is, for example, never possible to know in detail the fracture structure of the host rock or to be certain about the future climate. Repository safety must therefore be evaluated in the light of shortcomings of this kind. 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 is dependent on how methodically the uncertainties/deficiencies have been handled.

4.1.3 Steps in the safety assessment

The execution and presentation of SR 97 can be divided into five steps:

1. **System description**
   From the previous section it is apparent that a systematic analysis requires a structured description of all internal processes, their interrelationships and the properties of the repository that are influenced by a particular process. Preparing such a system description is therefore the first task in a safety assessment. This task also includes defining the boundary between a system and its surroundings.
2. **Description of initial state**
   The initial state of the repository, i.e. what it looks like when it has just been closed, is then described. This includes a description of the dimensions and materials in the engineered portions of the repository (fuel, canister, buffer/backfill) and the structure and properties of the geosphere around the repository as they appear initially.
3. **Choice of scenarios**
   The evolution of the repository is influenced by its surroundings. Assessments of the evolution of the surroundings necessarily contain uncertainties: What climatic conditions can be expected in the future? What frequencies and magnitudes of earthquakes can be expected in the repository's surroundings in the future? To cover different situations in the surroundings, the evolution of the repository is analyzed for a number of different sequences of events in the surroundings: a number of different scenarios are selected and analyzed. The chosen scenarios should together provide reasonable coverage of the different evolutionary pathways the repository and its surroundings could conceivably take.
4. **Analysis of chosen scenarios**
   With the aid of the system description, the evolution of the repository is analyzed for each of the chosen scenarios. A number of different tools and methods are used here, ranging from reasoning and simple approximations to detailed modelling based on site-specific data.

5. **Evaluation**
   Finally, an overall assessment is made of repository safety, where the different scenarios are weighed together into a total risk picture. The conclusions of the overall assessment comprise the results of the safety assessment. Confidence in the results in the light of the uncertainties that exist in the data underlying the assessment must also be discussed here.

The methodology used for the various steps is discussed in greater detail in coming sections.

4.2 System description

A systematic analysis requires a description of all known internal processes of any conceivable importance, their interrelationships and the properties of the repository that are influenced by the particular process. The structure of the description should provide both an overview and details. Another requirement on the structure is that it must be able to be used throughout in the presentation of the safety assessment. Previously, interaction matrices have been utilized to describe the system of internal processes. The description has largely been independent of the rest of the assessment and difficult to integrate into the report. Partly for this reason, a new structure for system description has been developed in SR 97.

4.2.1 System boundary

A prerequisite for the system description is that the boundary of the system be defined. The system description in SR 97 covers the engineered portions of the repository, i.e. fuel, canister and buffer as well as the geosphere in the immediate surroundings of the repository. This includes the upward extent of the geosphere to the ground surface approximately 500 metres above the repository and its extent to roughly the same distance in other directions from the repository. It is not meaningful to determine an exact, generally applicable limit to the extent of the geosphere in different directions. Necessary delimitations are instead done as needed in the appropriate subanalyses.

The surroundings, e.g. the biosphere or the distant parts of the geosphere, are studied in varying degrees of detail as needed. The distant parts of the geosphere need to be described accurately in connection with, for example, an earthquake analysis. Different aspects of the biosphere and its evolution are important in the event of a release of radionuclides from the repository.

One reason to make a clear distinction between the repository system and its surroundings is that the safety functions are associated with the repository system. Another reason is to be able to show whether the repository is robust, by which is meant that the internal evolution of the repository, particularly of safety-related aspects, is relatively independent of events in the surroundings. Regardless of climatic conditions, earthquakes and other external developments, the repository system should retain its isolating and retarding functions.

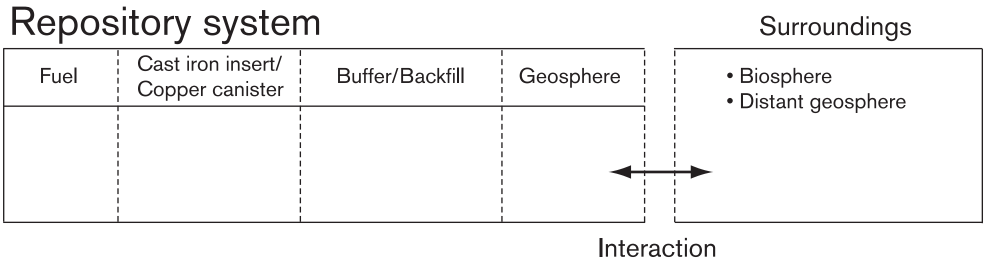

Figure 4-2. The repository system consists of the subsystems fuel, canister, buffer/backfill and geosphere. Since the internal subsystems are completely surrounded by the external ones, the repository can be represented "one-dimensionally" as in the figure.

4.2.2 Four subsystems

In looking for a structure for the system description, it is noted that the repository system consists of a number of consecutive barriers or subsystems where the internal subsystems are completely surrounded by the external ones. Innermost in the system is the fuel. All fuel is surrounded by canisters, all canisters are surrounded by buffer and backfill material in tunnels and shafts. All buffer and backfill is surrounded by geosphere. Outside the geosphere is what is meant by the "surroundings", consisting of the biosphere etc. This means that the system can be represented "one-dimensionally" with four subsystems that directly border on and interact with each other, see Figure 4-2.

Buffer and backfill have been described as a single subsystem for two reasons: Firstly, they have similar composition and properties, and secondly, a situation is then obtained where buffer and backfill only border outwardly on the geosphere. If buffer and backfill were described as separate parts, the buffer would border on both geosphere and backfill, and the simplicity of the one-dimensional description would be lost.

4.2.3 THMC interactions and processes

To lend further structure to the description, it can be noted that two subsystems, e.g. buffer and rock, mainly influence each other thermally (by heat flow), hydraulically (by above all water flow when the buffer absorbs water from the rock), mechanically (when the buffer swells due to water uptake and then exerts a swelling pressure on the walls of the deposition hole) and chemically (above all by exchange of solutes between groundwater in the rock and pore water in the buffer). The different processes that occur within a subsystem are also primarily thermal, hydraulic, mechanical or chemical by nature. This is illustrated in Figure 4-3 for buffer/backfill. The description also permits a clear distinction to be made between processes within a subsystem and the interaction between different subsystems. The interaction or process categories thermal (T), hydraulic (H), mechanical (M) and chemical (C) are often referred to collectively as THMC in the literature. This designation is also used in SR 97.

Since the assessment concerns a system where radiation from radioactive materials plays a principal role, radiation-related interactions and processes also enter in, particularly radioactive decay in the fuel and attenuation of the radiation that is emitted from an intact canister. A fifth category, radiation-related processes (R), is therefore added to the THMC processes.

A large portion of the assessment is concerned with radionuclide transport, which is also important for evaluation of the safety of the repository. Radionuclide transport is in fact a collective consequence of a number of hydraulic and chemical processes and is therefore covered by the processes in these categories. If the chemical and hydraulic conditions as well as the fracture geometry in the geosphere are known, radionuclide transport can be described. Since radionuclide transport comprises such an important part of the safety assessment, the different subprocesses involved in radionuclide transport have never-theless been gathered in a special category in each subsystem, see Figure 4-3.

Microbial processes occur in buffer/backfill and in the geosphere. They have been categorized among the chemical processes. Another option would have been to have a special category for biological processes. This has been avoided because there are few biological processes, and because they are of limited importance for the evolution of the system at depth. Biological processes in the biosphere-geosphere interface have though a decisive influence on the composition of the water that penetrates down into the bedrock from the biosphere.

It is not always self-evident which category a process should be assigned to, just as there are no clear-cut limits between different fields in the natural sciences. The categorization is mostly an aid in visualizing lines in the system structure. In doubtful cases, the category considered to be the most expedient for obtaining a clear and distinct system description has been chosen.

4.2.4 Which processes?

All relevant processes can be arranged in the above structure. The set of processes used in SR 97 has been taken from earlier work with interaction matrices, where processes and interactions of importance for the evolution of the repository have been identified in another format in a near-field matrix (fuel, canister and buffer) and a far-field matrix (geosphere). There is also a more detailed matrix for buffer alone. All matrices are documented in a database /Pers et al, 1999/.

The material in the matrices can be either processes within a subsystem, interactions between subsystems or descriptions of the initial state. The three occur without clear distinction.

Almost all information in the matrices has been arranged in THMC structures of processes and interactions or included in the description of the initial state. This is documented in Pers et al /1999/.

The material in the interaction matrices has also in part been linked to and checked against SKB's FEP database, which contains features, events and processes of importance for the evolution of the repository. The database has been developed as the work with interaction matrices has progressed. Similar information from organizations the world over is gathered in an international database compiled by the OECD/NEA /NEA, 1997b/.

After SR 97, the use of interaction matrices, THMC diagrams and databases will be evaluated to determine the role of these different tools in future assessments.

The question of completeness also has a bearing on the choice of processes. Have all relevant processes been identified? The question is further discussed in section 4.6.1.

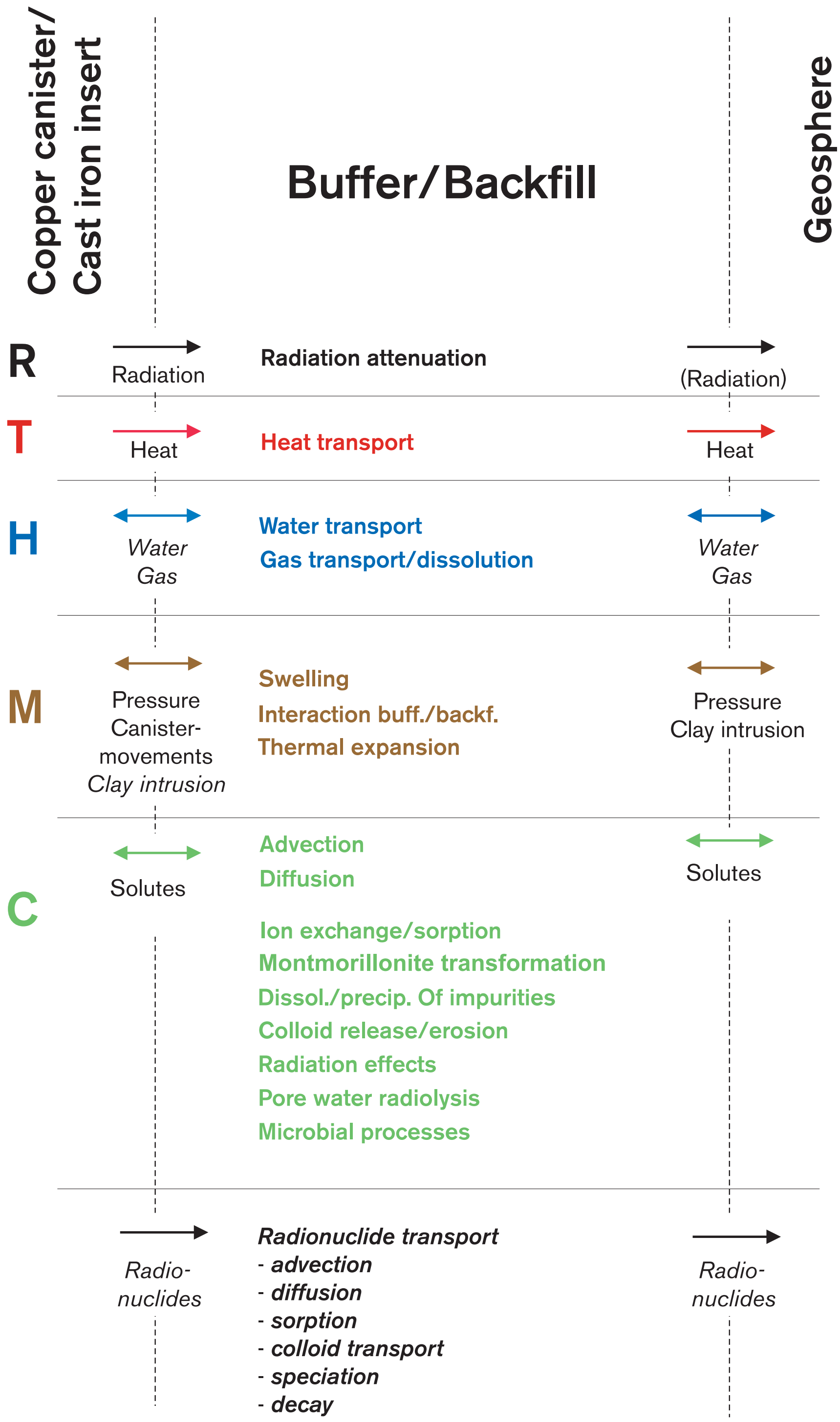

Figure 4-3. THMC processes in buffer/backfill. The figure also illustrates the interaction between buffer/backfill and surrounding repository parts broken down into T, H, M and C. Radiation-related processes/interactions (R) are also included, along with radionuclide transport.

Ranking of processes?

In the interaction matrices, processes and interactions have been ranked on a three-degree qualitative scale. This information has not been transferred to the system description. Instead, the long-term ambition is to quantify as many of the processes as possible, or to show that a process is of negligible importance for the evolution of the repository under all conditions.

4.2.5 Documentation of processes

The system description also includes documentation of knowledge concerning each process. Such documentation constitutes a cornerstone in the background material for a safety assessment.

Knowledge of all identified processes in the system description is documented for SR 97 in the Process Report. The following are given for each process:

- general description of the process,
- documentation of model studies/experimental studies,
- discussion of uncertainties in both understanding and data for the process,
- proposals as to how the process can be handled for different scenarios in the safety assessment

The documentation is a first version, which will be revised in certain aspects for coming assessments. The intention is to gradually arrive at a permanent system description with appurtenant process documentation, all collected in a purpose-suited database.

4.2.6 Variables

The state in a subsystem is characterized at any given moment by a set of variables (bold in the examples given below). The state of the geosphere is, for example, characterized by its temperature, which varies in time and space, by its fracture geometry (which varies widely in space, but hardly at all in time), by groundwater flow, groundwater composition, rock stresses, etc.

Together, the variables should characterize the system sufficiently well to enable a safety assessment to be conducted. Some variables, such as temperature and groundwater composition, are used or determined directly in analyses and calculations, while others serve as a basis for deriving important properties of the system: The thermal conductivity and density of the geosphere can, for example, be calculated from the variable matrix minerals. The variables should also be independent of each other, in order to provide a clear-cut description of the coupled system of processes.

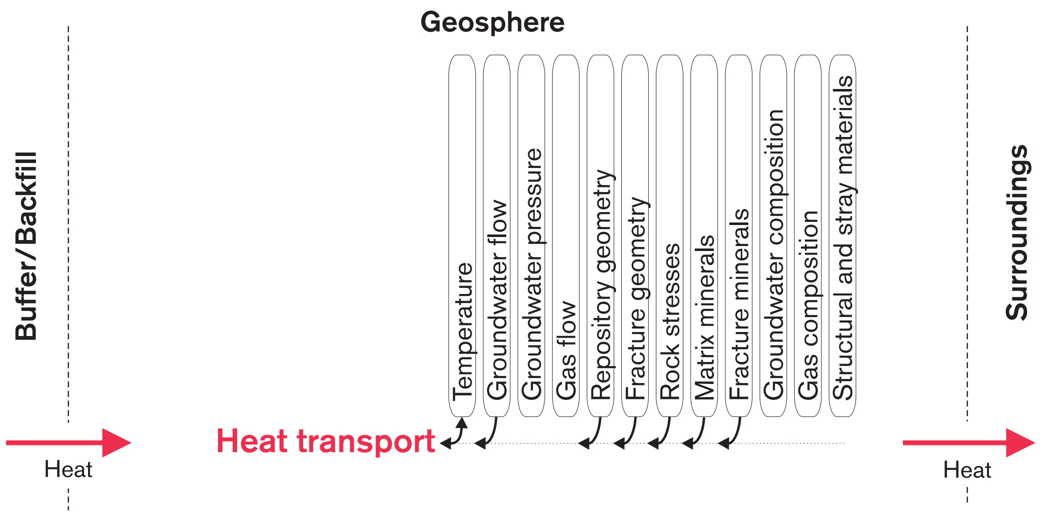

Figure 4-4. *Heat transport in the geosphere.*

All variables are influenced by one or more processes, and all processes are influenced by one or more variables. The process heat transport in the geosphere, Figure 4-4, serves as an example: Heat transport takes place principally by heat conduction, and the thermal conductivity of the geosphere is determined by the mineral composition of the rock matrix or by the state variable matrix minerals, which thus influences heat transport. Heat can also be transported to some extent with the flowing groundwater (heat flow), and the groundwater flow therefore influences heat transport. The temperature both influences and is influenced by the processes: Heat transport changes the temperature, but the temperature difference between different parts of the geosphere is also the very driving force for the transport process. Finally, the geosphere's geometric boundary with the canister holes must also be included in the description of heat transport, since the heat flow from buffer and backfill to the geosphere is the most important source of heat transport. This is expressed by the variable repository geometry/boundary.

4.2.7 THMC diagram

The complete diagram for the geosphere is shown in Figure 4-5, which also shows how the geosphere interacts with buffer and backfill and with the surroundings. To emphasize the subdivision into thermal, hydraulic, mechanical and chemical processes, this way of describing the system has been called a THMC diagram. A more detailed discussion of the THMC diagrams for the different subsystems is found in Chapter 5.

The THMC diagram with all processes, variables and relationships between them may appear complex. As will be evident from Chapter 8, however, there are clear principal features in the system which greatly simplify the analysis. One important such principal feature is that the evolution can be divided into thermal, hydraulic, mechanical and chemical components which influence each other via a few important couplings. This is another strong reason for using a THMC structure in the system description.

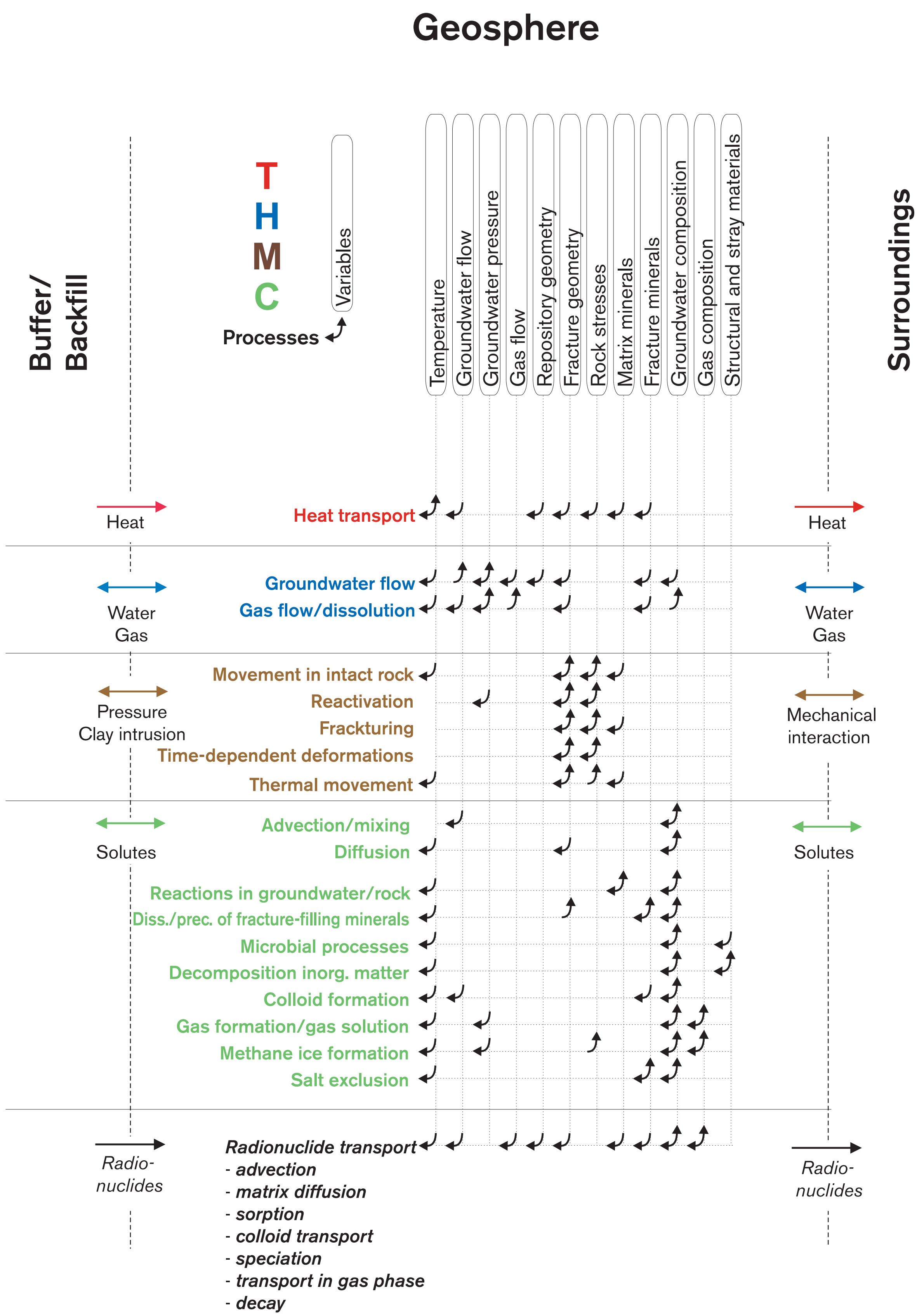

Figure 4-5. THMC diagram for the geosphere.

4.2.8 Universal format

As mentioned previously, the approach is a general one in the analysis of systems that change with time: A system is delimited by a system boundary and an initial state is determined. Thereafter the evolution of the system is determined by time-dependent internal processes and by interaction with the surroundings. The description is also valid for subsystems: The evolution in buffer/backfill, for example, is given, if the initial state is known, by time-dependent internal processes and interaction with the surroundings, in this case canister and geosphere. A number of processes proceed simultaneously in each subsystem. The processes change the state and the state is expressed by the variables.

To further clarify the format for the system description, let us consider a chemical plant using the same terminology. The plant is conceived as being made up of a few subsystems in the form of, for example, different reaction vessels. A number of processes proceed simultaneously in each reaction vessel, such as heating, chemical reactions and stirring. Each vessel is also equipped at several places with measuring instruments which show temperature, pressure, liquid and gas flows, concentrations of raw materials and reaction products, etc. The plant has an initial state at the start of production, including original temperature, concentrations, etc.

The subsequent evolution in the plant is driven by the processes in the different subsystems. The state in time and space in the plant can be monitored on the different instruments, where it is also possible to check whether anything undesirable is happening, for example by the fact that a temperature or a concentration is higher than a given limit value. The different subsystems influence each other, for example the reaction products from one vessel are transferred to another where they serve as raw materials. The entire plant also interacts with its surroundings, for example raw materials are delivered to the plant and finished chemical products are dispatched from the plant.

While the processes in chemical plants can proceed rapidly and a great deal can happen in a day, an hour or even a few seconds, changes occur much more slowly in the deep repository system. No energy to speak of is pumped into the processes, most processes proceed very slowly, and the radiotoxicity of the fuel declines steadily.

4.3 Initial state

Once the system description has been completed, the next step is to describe what the repository looks like when it has just been closed, i.e. its initial state. This includes the design of the fuel and its content of radionuclides, the dimensions and materials used for the cast iron insert and copper canister, the composition of buffer and backfill, the geometric dimensions of deposition holes, tunnels and shafts, the fracture structure, temperature, groundwater flow and groundwater composition in the geosphere, etc.

The description of the initial state is thereby also an abbreviated site description, tailored to the needs of the safety assessment.

The description follows the structure of the system description in that the different variables are assigned initial values. Much of the information can be obtained from the repository specifications, for example the design of the copper canister. Other aspects, for example the structure of the fracture system, are site-specific and must be determined by measurements in the field. Certain conditions change rapidly, e.g. the temperature in the buffer immediately after deposition, while others can be expected to retain their initial values with little variation over long timespans.

The description of the initial state also includes specifying uncertainties in the determinations of the different variables. In general, the uncertainties can be said to be relatively small for the variables that describe the engineered parts of the repository and much bigger as far as conditions in the geosphere are concerned.

Three different sites are assessed for SR 97. In the report they are called Aberg, Beberg and Ceberg. The initial state for each of these must thus be described.

The initial state used in SR 97 is presented in Chapter 6. Most of the material in Chapter 6 is taken from the Repository System Report.

4.4 Choice of scenarios

With the system of processes defined in the system description, the repository's evolutionary pathway is determined if

a) an initial state and

b) the conditions in the surroundings (ambient conditions)

can be determined. Both initial state and ambient conditions are, however, associated with uncertainties.

Current external conditions can be observed and described. This includes, for example, what the biosphere above the repository looks like, the climate and the structure of society. On the other hand, great uncertainty exists with regard to how climate, biosphere and above all society will change in the future. The consequences of such changes for the repository must nevertheless be analyzed. The method used for this is to analyze the evolution of the repository for a number of possible future situations in the surroundings. A set of different scenarios is analyzed.

A scenario is thereby defined as the sequence of events undergone by the repository system given an initial state and specified conditions in the surroundings.

A critical step in the assessment is choosing a number of scenarios which are then subjected to analysis. Together, the chosen scenarios should provide reasonable coverage of the different evolutions the repository and its surroundings might conceivably undergo.

The description of the initial state also includes uncertainties that should be covered by the choice of scenarios. Many such uncertainties have limited importance for the evolution of the repository. The importance of others may need to be illuminated by analyzing different variants of a scenario, distinguished for example by different interpretations of the fracture structure in the geosphere. There is, however, at least one important initial condition that is of crucial importance for the evolution of the repository: if one or more of the canisters should have such undetected defects from fabrication that waste isolation is jeopardized from the start.

Such crucial uncertainties in the initial state can also be handled by analyzing different scenarios, in this case where a few canisters are assumed to have fabrication defects. Postulating that a few canisters are initially defective is also a way to investigate the retarding function of the repository.

In SR 97, five scenarios have been chosen for detailed analysis. The selection is based on experience from the work with interaction matrices, the FEP database and the system description. These systematic analyses of the repository system have yielded a set of factors that can affect the performance and safety of the repository. Experience from previous safety assessments by SKB and other organizations has also been drawn on.

The system description has been developed during the work with SR 97 and has not been fully utilized for a systematic choice of scenarios. The description has, however, been used to systematize the descriptions of the initial state as a set of variables and interactions with the system's surroundings under different conditions in the form of THMC interactions. This has made it possible to systematize the scenario description to a higher degree than previously.

4.4.1 Scenarios in SR 97

It will be helpful to the further methodology discussion to define here the scenarios that have been chosen in SR 97. More thorough definitions of the premises for the different scenarios are given in Chapter 7.

The scenarios chosen for SR 97 are:

- A base scenario where the repository is conceived to be built according to specification, where no canisters have initial defects and where present-day ambient conditions are assumed to exist.
- A canister defect scenario which differs from the base scenario in that a few canisters are assumed to have initial defects.
- A climate scenario that deals with future climate-induced changes.
- An earthquake scenario.
- A scenario that deals with future human actions that could conceivably affect the deep repository.

The climate scenario is studied for two possible assumptions: when all canisters are initially intact and when a few canisters have initial defects.

4.4.2 Probability of a given scenario occurring; Variants

The criterion for repository safety is formulated as a risk limit. This means that both the probability and the consequence of a given sequence of events (scenario) must be assessed, see also section 4.6.5. Such a probability must therefore be arrived at for each scenario description.

Each scenario covers an infinite number of possible evolutionary pathways with the same principal features. Small differences in the deposition sequence lead, for example, to variations in the thermal evolution in the geosphere. Nevertheless, all such variations have the same principal features and are covered by the thermal evolution in e.g. the base scenario. The probability that a particular evolutionary pathway will actually occur approaches zero if the premises (including the initial state) are described in sufficient detail. The probability associated with a given scenario is the probability that the principal features will be realized and is theoretically the sum of the probabilities of all the premises covered by the scenario.

In SR 97, the probabilities of the scenarios are discussed in the last step of the assessment, evaluation of results. This is done when the results of all scenarios are weighed together to arrive at an overall risk analysis.

A scenario may sometimes have to be divided up into a number of variants, each with its own probability. This becomes particularly evident in probabilistic analyses, see further section 4.6.5.

The borderline for when a variant differs enough to be called a separate scenario is a matter of definition. Where the borderline goes is, however, not important as long as the probability of each scenario and each variant is estimated and weighed together in the final risk analysis.

4.5 Analysis of chosen scenarios

After a system description has been prepared, the initial state described and a set of scenarios chosen, the actual analysis of the chosen scenarios begins.

The idea is to first analyze in detail the base scenario, where the repository is assumed to be built according to specification and where present-day ambient conditions are assumed to exist in the future as well. Then other scenarios are analyzed by examining differences compared with the base scenario.

How will the evolution of the repository change if the climate changes? In the event of earthquakes? If several canisters have fabrication defects? What importance do these changes have for safety? A basis for carrying out the analyses and reporting them in the form of comparisons with a base scenario is that the analyzed repository system is engineered to be robust, i.e. so that varying conditions in the surroundings do not cause dramatic changes in the evolution and performance of the repository.

4.5.1 Analysis of conditions in the surroundings

The evolution in the repository's surroundings is described and analyzed for each scenario. The methods for and depth of these analyses vary widely between the different scenarios. In the case of climate, for example, a simple description of today's climate in the form of annual mean temperature and annual precipitation is sufficient in the base scenario. In the climate scenario, on the other hand, a much deeper analysis is required of the dramatic changes that occur in connection with an ice age. Similarly, it is important to describe in detail the biosphere in the canister defect scenario, where release to the biosphere can be expected, while the biosphere description in the base scenario can be couched in much more general terms. The methodology for the description of conditions in the surroundings is presented as needed in each scenario analysis.

A general goal of the analyses of the surroundings is that they should result in a description of thermal, hydraulic, mechanical and chemical interactions with the repository system.

4.5.2 Base scenario

In the base scenario, the evolution of the repository is analyzed under the assumption that the present-day climate persists and no copper canisters have fabrication defects.

All relevant processes when the canisters are intact are handled in the base scenario. The breakdown of the complex system of processes and variables into thermal, hydraulic, mechanical and chemical components with a few important couplings between them is also shown in the scenario, Figure 4-6. The figure is explained in greater detail in Chapter 8.

The process documentation is used to evaluate and assess the importance of different processes for repository evolution. Certain courses of events, such as the temperature evolution of the repository and the groundwater flow in the geosphere, are studied by means of modelling performed specially for SR 97. Other processes, such as the scope of copper corrosion or certain structural changes in the buffer, can be handled with simple rough calculations. Pessimistic data are often used in modelling and rough calculations so as not to overestimate the protective function of the repository.

The analysis ends with an evaluation of repository safety for the base scenario. The emphasis in the analysis lies on evaluating the repository's primary safety function of isolating the fuel.

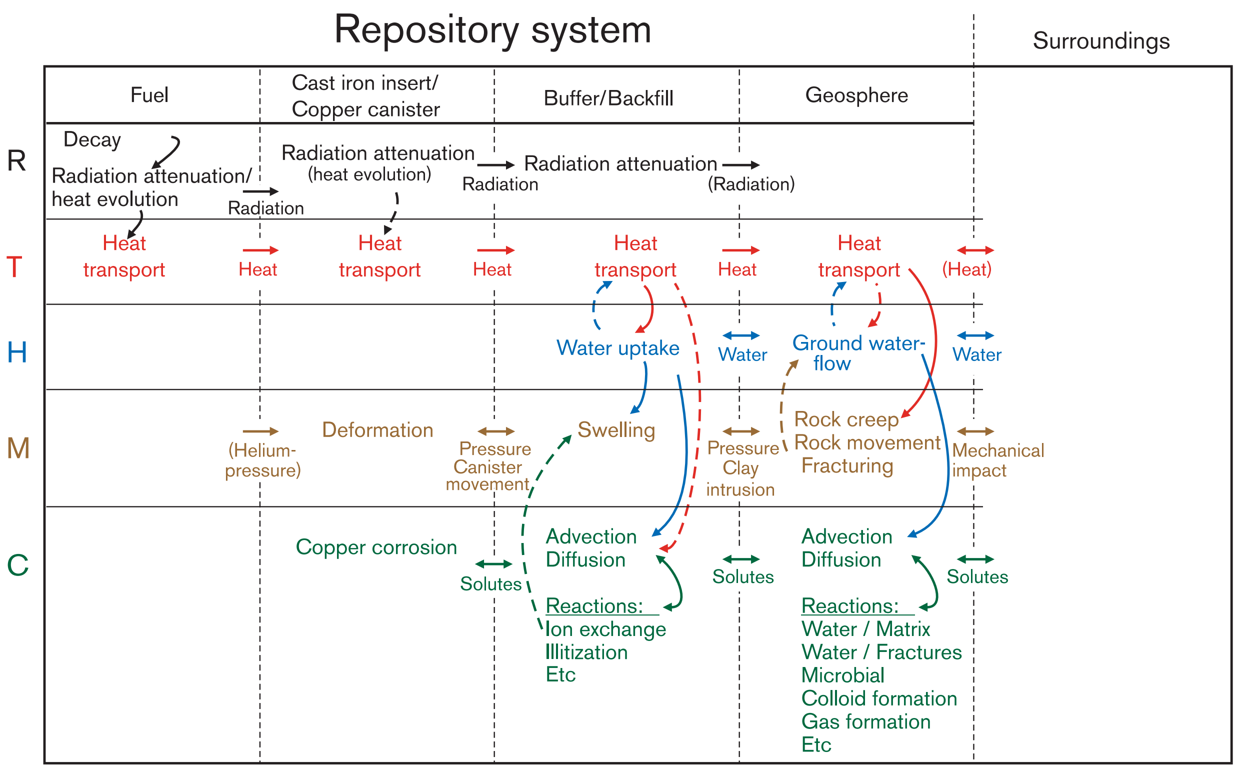

Figure 4-6. The most important processes and couplings in the base scenario.

4.5.3 Canister defect scenario

The course of events in the canister scenario is the same as in the base scenario except for the few canisters which are assumed to have initial defects. The internal evolution of such a canister is analyzed by means of modelling, while the canister's surroundings can largely be expected to remain unaffected, with one important exception: Radionuclides can escape from the defective canister after some time.

The primary safety function, isolation, is disabled for these canisters and the emphasis in the analysis switches to the secondary function: retaining and retarding the outward transport of radionuclides. Here quantitative questions become important: To what degree are the radionuclides retarded in canister, buffer and rock? Do they have time to decay before reaching the biosphere? If not, what will the consequences be for man and the environment? Detailed quantitative analyses of groundwater flow in the geosphere, transport through canister, buffer and geosphere and radionuclide flux in the biosphere result in quantitative estimates of doses and risks for humans in the vicinity of the repository. The results are compared with official acceptance criteria.

More can be read about the methodology for the calculations of radionuclide transport in sections 4.6.4 and 4.6.5.

4.5.4 Other scenarios

The analysis of other scenarios is aimed at comparing the evolution of the repository when major external changes are assumed, with the evolution in the base scenario. Studying the influence of e.g. an ice age also requires analyses of e.g. the growth of a continental ice sheet during a glaciation. The methodology used for this is described briefly in each scenario, Chapters 10–12. Here as well, the analysis has been broken down into thermal, hydraulic, mechanical and chemical aspects. For each scenario, the interaction between the repository and the surroundings has been described in the form of THMC interactions. If the evolution leads to canister damage, calculations of radionuclide transport are also carried out.

The course of events if the initial state includes canisters with defects is also analyzed in the climate scenario.

4.6 Handling of uncertainties

The background data for a safety assessment is necessarily burdened with different types of deficiencies and uncertainties. An important part of the assessment is therefore the handling of such deficiencies. This is not a separate activity, but comprises an integral part of the analysis work. Uncertainty handling is nevertheless discussed independently here, since it comprises an important part of the methodology.

Deficiencies can be of a qualitative or quantitative nature. Qualitative deficiencies concern e.g. questions of completeness: Have all processes that influence the evolution of the repository been identified in the system description? Have all types of external impact been covered in the choice of scenarios? Other qualitative questions concern process understanding: Do we understand the internal processes well enough for the needs of the safety assessment? Do we understand the processes that determine conditions in the surroundings well enough?

Table 4-1. The types of uncertainties that enter into the first four steps of the analysis and where they are reported and handled.

1. System description	
Completeness	Discussed in section 5.8.
Process understanding (conceptual uncertainty)	Described in detail in a separate report, the Process Report.
2. Description of initial state	
Data uncertainty	Quantitative uncertainties in the initial state are described for each variable in Chapter 6.
3. Choice of scenarios	
Completeness/Coverage	Discussed in section 7.3.
4. Analysis of chosen scenarios	
Model uncertainty (conceptual uncertainty)	General confidence in models used is discussed briefly where model studies are reported in the scenarioanalyses in Chapters 8–11. Confidence in models for radionuclide transport and groundwater flow is discussed more thoroughly in section 9.11.
Input data to models/ calculations	General data uncertainties are discussed briefly where calculations and model studies are reported in the main report. Data uncertainties that concern radionuclide transport and groundwater flow are reported and discussed in detail in a special Data Report. Uncertainty analyses and probabilistic analyses are done in the calculations or radionuclide transport.

Other questions are quantitative. How well can we determine the initial state? The initial temperature of the repository can be determined with an accuracy which is fully adequate for the needs of the analysis, while the description of fracture geometry in the geosphere is burdened with uncertainties that require more careful handling. How well can we describe different processes quantitatively, for example heat conduction or groundwater flow? This question is particularly important for the analysis of radionuclide transport, which is of direct importance to the evaluation of the repository's safety. Calculations of radionuclide transport handle large amounts of input data, which may be burdened with varying degrees of uncertainty.

A deeper discussion of different types of uncertainties is held in the safety report SR 95 /SKB, 1995/.

Handling of uncertainties consists of both reporting uncertainties and deficiencies in the underlying data and handling them when conducting the analysis. Table 4-1 shows the different types of uncertainties which enter into the different steps of the analysis. The uncertainties are discussed in brief in the following.

4.6.1 Completeness in system description and choice of scenarios

It is never possible to prove that all processes, variables and couplings of importance have been identified in a system description. Confidence that the scope of the description is adequate for the needs of the safety assessment must instead be judged. The efforts that have been made to achieve a complete description and the arguments for why the scope of the description should be adequate are described in the analysis. Confidence that the scope is adequate for the purpose of the safety assessment will then be judged. The efforts that have gone into obtaining a full-coverage system description in SR 97 are described in section 5.8.

A similar situation exists for completeness and degree of coverage in the choice of scenarios. This is discussed in Chapter 7.

4.6.2 Quantification of initial state

An explicit initial state is described in SR 97 in the form of a number of variables which are given initial values. Uncertainties are also discussed for each variable.

The initial state is the point of departure for modelling of repository evolution and thereby constitutes a portion of the input data required for modelling not just of radionuclide transport but also of other processes in e.g. the base scenario.

The description of uncertainties in the initial state is also a basis for the choice of scenarios as described above.

The initial state can also be said to be a quantification of the chosen repository design. If the safety assessment is to be utilized to discuss consequences of changes in design, the initial state with uncertainties can be a basis for such discussions.

For these reasons, among others, a special account of uncertainties in the initial state has been given in SR 97.

4.6.3 Conceptual uncertainty

The term "conceptual uncertainty" is used in SR 97 both for the uncertainties stemming from the fact that the fundamental understanding of a process is not complete and for the uncertainties caused by the fact that a mathematical model does not correctly describe a process (of which we may nevertheless have a good fundamental understanding).

Fundamental understanding

The understanding of each process identified in the system description is discussed and presented in the Process Report. Here it is important to have the proper perspective: to understand the process thoroughly enough for the purpose of the safety assessment. Often, an incomplete understanding of a process can be handled in the safety assessment by overestimating the consequence of the process.

An example: The fuel is enclosed in cladding tubes of Zircaloy, a durable alloy. If a copper canister should be damaged and water should reach the cladding tubes, they will begin to corrode. The long-term course of the corrosion process is not completely understood. The barrier function of the cladding tubes is therefore usually pessimistically disregarded in the safety assessment. In this way the consequences of the corrosion process for the escape of radionuclides from the canister is overestimated.

Another example is the process of illitization, a long-term chemical transformation of the buffer. There are several prerequisites for this process to take place. One of them is availability of potassium. All the details of the process are not known, but it is known for certain that the transformation cannot proceed faster than is permitted by the supply of potassium. The scope of the process can therefore be pessimistically calculated as if only the supply of potassium was limiting, something which can be calculated relatively easily.

Model uncertainty

Even if the fundamental understanding of a process is good, it isn't certain that a satisfactory mathematical model of the process can be formulated to be used in the safety assessment. Groundwater flow can serve as an example: The fundamental laws of nature which control groundwater flow in fractured rock are well known, as is also evident from the Process Report. For the purpose of a safety assessment, on the other hand, knowledge of the structure of the fracture system on different scales is inadequate. It is therefore necessary to introduce new (e.g. statistical) model concepts to be able to carry out a modelling despite these shortcomings.

Model uncertainty is thus related to the question of whether a given model describes reality sufficiently well for the needs of the safety assessment. In SR 97, confidence in the models used in analyses of groundwater flow and radionuclide transport are discussed in the canister defect scenario, Chapter 9.

4.6.4 Uncertainties in input data for radionuclide transport calculations

Reasonable and pessimistic values and statistical distributions

The results of the radionuclide transport calculations quantify repository safety. It is thereby particularly important to assure the quality of these calculations, and the handling of uncertainties in input data must be rigorous. Figure 4-7 shows the models (rectangles) and the input data (ellipses) that are used in radionuclide calculations in SR 97. An ellipse can often represent a large set of data, e.g. specific values for each radionuclide, or each chemical element that is handled in the calculation.

Each such set of input data is taken from background reports by experts within the relevant field. Many of the reports have been specially produced for SR 97. Each author has discussed uncertainties in data according to a given template.

The discussion of uncertainties in the individual reports has then been evaluated in the Data Report. This document has also proposed for almost all input data:

- a reasonable value and
- a pessimistic value.

In addition to a reasonable and a pessimistic value, distributions of possible values have also been presented for some input data, such as data that exhibit spatial variability or data determined by spatially variable conditions. In the geosphere, the heterogeneity in e.g. the fracture system gives rise to a distribution in space of various data for calculations, often after extensive analyses.

The span between reasonable and pessimistic values offers an option for representing uncertainties in input data. In the few cases where distributions are available, the distribution chiefly represents uncertainties caused by the spatial variability. Radionuclide transport calculations are carried out with different combinations of reasonable and pessimistic data in order to shed light on the importance of different uncertainties. Furthermore, probabilistic analyses are performed, which is the subject of the next section.

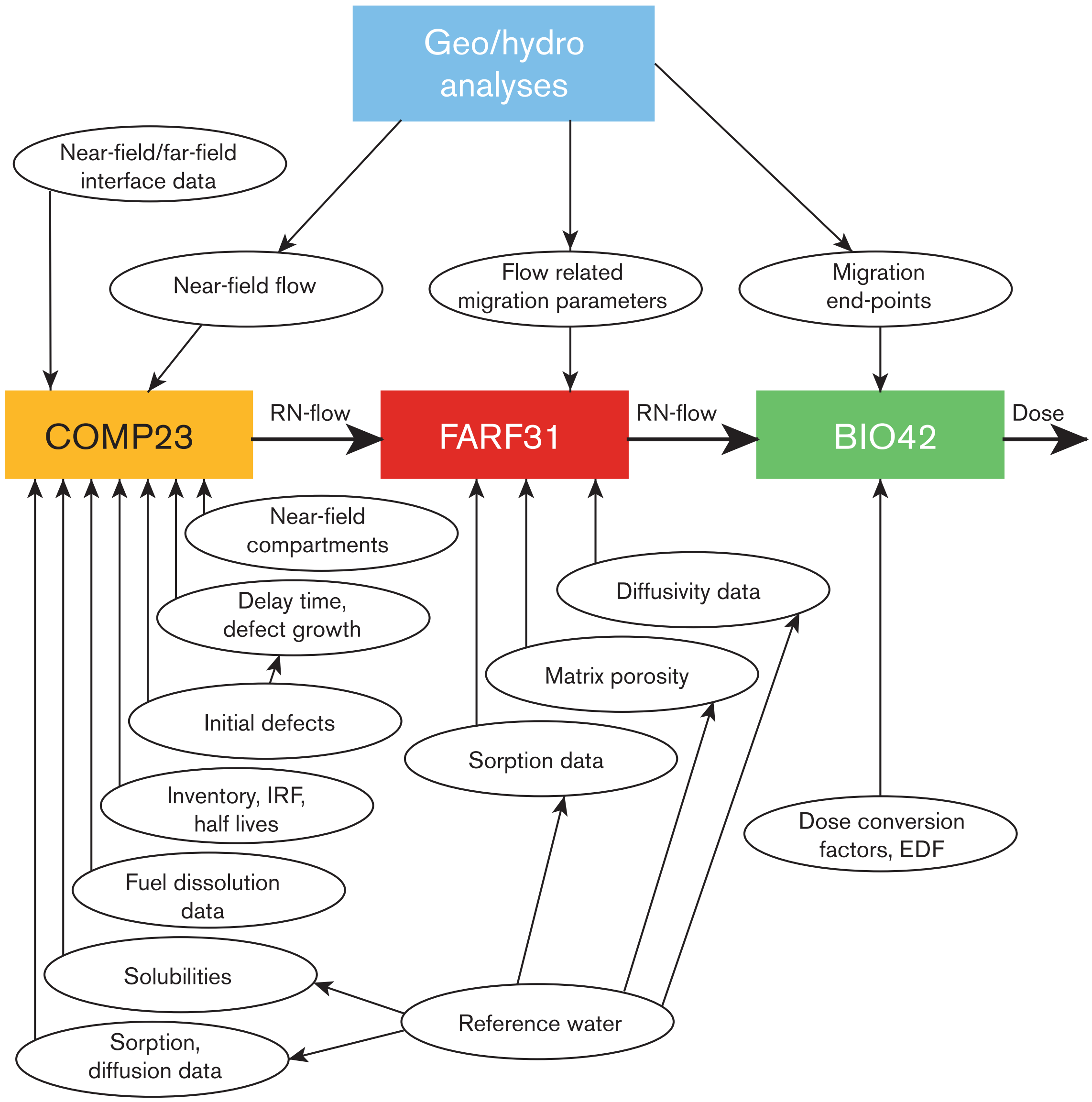

Figure 4-7. *Models (rectangles) and input data (ellipses) in radionuclide transport calculations.*

4.6.5 Probabilistic calculations

The acceptance criterion for a deep repository is formulated as a risk criterion. This means that both probability and consequence must be estimated for a conceivable sequence of events. Probability and consequence are multiplied to obtain a risk and the risks for all analyzed sequences of events are added to obtain a total risk, which is compared with the acceptance criterion.

This can be done in different ways. One possibility is to estimate an upper limit for the probability of each scenario and then calculate a consequence with pessimistically chosen values for all relevant data. The consequence is multiplied by the probability to obtain a pessimistic risk measure, i.e. one that should overestimate the risk. The risks from the different scenarios are then added together to obtain a total risk measure.

Another possibility is to adopt a probabilistic approach within a scenario as well, i.e. to carry out a probabilistic consequence calculation. In the extreme case, probability distributions are given for all relevant data that are not known exactly. A large number of different realizations of the consequence calculation are carried out, where input data are taken randomly from the reported distributions. Each realization results in a consequence, e.g. a dose, and all realizations are equally probable. The aggregate result is a statistical distribution of doses, and the risk is equal to the mean value of the distribution. This is called conditional risk, since it is conditional on the scenario in question having occurred. The unconditional risk is obtained by multiplying by the probability that the scenario will actually occur. The aggregate risk is as before the sum of the unconditional risks for all scenarios.

In this way the probabilistic element can be made larger or smaller in the consequence calculations in a safety assessment. Different countries and organizations have elected their specific approach, often as a reflection of the laws and regulations in each country.

The use of probabilistic methods and analyses in a safety assessment is a topic of international discussion, see for example NEA /1997a/. The computer programs used for the calculations in SR 97 can handle probabilistic calculations, and such calculations are also performed.

The probabilistic methodology in SR 97 is designed in light of the fact that distributions are lacking for the vast majority of input data.

Solubilities for different chemical elements can serve to illustrate the difficulty of determining distributions. The solubility of a chemical element in a water-filled canister often sets a fundamental limit on the outward transport rate of the element in question. Solubilities used in the safety assessment are determined by separate calculations based on the composition of the groundwater and the properties of the chemical element.

Both these factors are determined by quantities of data from site-specific measurements of groundwater and experimentally or theoretically determined constants. These primary data are themselves associated with uncertainties which require expert judgement to be used reliably in the calculation of solubilities.

In this situation it has been deemed appropriate to report, by evaluating underlying uncertainties, a reasonable and a pessimistic value for the solubilities used in the radionuclide transport calculations.

If a fully implemented probabilistic approach had been used, an attempt would instead have been made to estimate a probability distribution of solubilities for each element. It has been deemed to be very difficult to arrive at a reliable distribution of possible values for solubility. The difference is illustrated in Figure 4-8. The same applies to other types of chemical input data determined by similar procedures as solubilities.

The situation becomes even more complicated when one bears in mind that correlations between different distributions must also be described for a correct stochastic treatment. In the example with solubilities, a distribution is determined for each relevant chemical element. Certain factors that influence solubility are the same for all elements, for example those that have to do with the chemical environment. In this way, the distributions are to some extent correlated, and this must also be described quantitatively in order for the result of a probabilistic calculation to be correct.

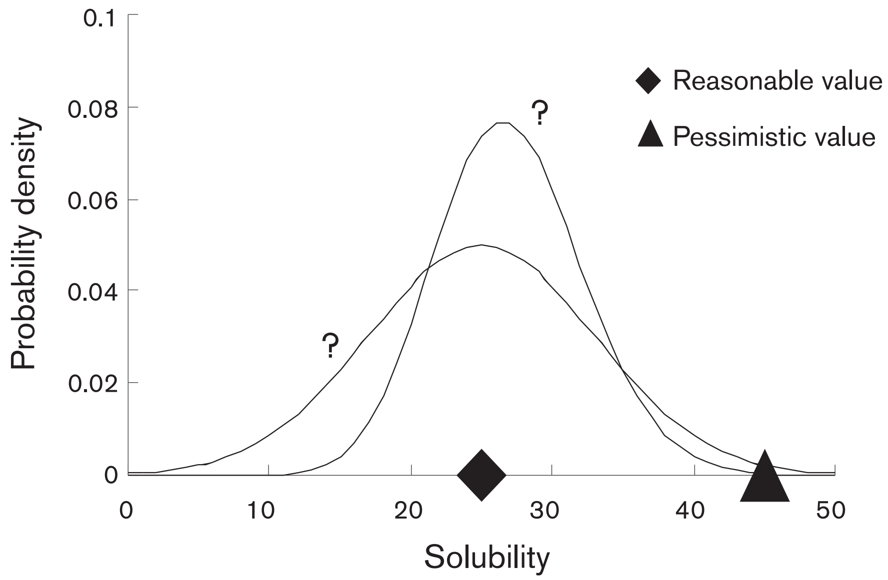

Figure 4-8. *A reasonable and a pessimistic value have been estimated for e.g. solubilities of different elements. It has however not been deemed possible to define a probability distribution for the solubility.*

Risk calculations for a deep repository contrast here with calculations for many technical systems where statistics from operating experience can serve as a basis for a probabilistic analysis. In a safety assessment of, for example, the operation of a nuclear power plant, operating statistics for pumps and standby generators can provide data for a probabilistic analysis.

In SR 97, distributions have only been used where there is some kind of statistical material on which to base a distribution. This includes:

- Conditions in the geosphere that are determined by the spatial variability of the geosphere. These may include primary conditions such as fracture statistics or hydraulic conductivity, or data calculated on the basis of the spatial variability, e.g. water travel times.
- Positions for initially damaged canisters in the repository.
- Earthquake statistics for the earthquake scenario.

In other cases, such as solubilities, the uncertainty largely stems from a lack of knowledge concerning what conditions will prevail. Here it can be generally said that values around the reasonable ones are much more probable than the pessimistic values. It is also possible to generally judge whether one quantity is correlated with other quantities.

Due to the difficulty of estimating distributions for all data, it is not possible to fully implement a probabilistic analysis. On the other hand, it is necessary to calculate a risk to compare with the acceptance criteria. The following approach is used in SR 97 for the probabilistic analyses:

- Statistical distributions are used only where there is some kind of statistical material on which to base a distribution, see the examples above.
- Reasonable and pessimistic values are used for other data. Both are assigned probabilities that are chosen so that the risk is deemed to be overestimated in the probabilistic analysis.

The method is described and discussed more in section 9.11.

In summary, the use of a stochastic body of data that rests on a weak foundation can undermine confidence in the results of the safety assessment. Probabilistically calculated results in the form of e.g. dose and risk distributions are also more abstract and thereby sometimes more difficult to interpret and explain, but are needed for the risk estimates that are necessary to assess the safety of the repository.

4.7 Coming work

SR 97 uses a new format for system description, with appurtenant documentation of processes. The format also permeates the presentation of the entire safety assessment. Some revisions should be implemented for coming assessments:

- A revision of the process selection based on available databases.
- Augmentation of the process documentation.
- A more systematic choice of scenarios based on the format for system description and available FEP databases.
- Storage of system description with appurtenant process documentation on electronic medium, coupled to existing databases.
- An evaluation of the method for probabilistic analysis.

Furthermore, the methodology for the safety assessment should be critically reviewed regularly in the light of methodology used in other safety assessments, new methods as they are developed, viewpoints from reviews of this assessment, etc.

4.8 References

NEA, 1997a. Lessons learnt from ten performance assessment studies. Nuclear Energy Agency Organisation for Economic Co-operation and Development.

NEA, 1997b. Safety assessment of radioactive waste repositories – Systematic approaches to scenario development – An international database of features, events and processes. Draft report (24/6/1997) of the NEA working group on development of a Database of Features, Events and Processes Relevant to the Assessment of Post-Closure Safety of Radioactive Waste Repositories. Paris, Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA).

Pers K, Skagius K, Södergren S, Wiborgh M, Bruno J, Pusch R, Hedin A, Morén L, Sellin P, Ström A, 1999. SR 97 – Identification and structuring of processes. SKB TR-99-20. Svensk Kärnbränslehantering AB.

SKB, 1995. SR 95 – Template for safety reports with descriptive example. SKB TR 96-05. Svensk Kärnbränslehantering AB.

5 System description; processes and variables

5.1 Introduction

In this chapter, the repository system is described in the special format that is to be used in the safety assessment, see section 4.2. In brief, this entails that the repository is divided into the four subsystems fuel, canister, buffer/backfill and geosphere. The processes that are of importance for the long-term evolution of the repository and the variables that are needed to characterize the subsystem are identified for each subsystem. The procedure for the choice of processes is also described in section 4.2.

This chapter begins with an overview of the KBS-3 system, followed by the following for each subsystem:

- a general description,
- an overview of variables,
- an overview of processes,
- a THMC diagram showing all processes and variables and the coupling between them.

The system description also includes an extensive documentation of each process. The documentation of all processes is gathered in the Process Report, whose format was described in section 4.2.

Together with the process documentation, the general descriptions in this chapter comprise the system description in SR 97. The system description can be said to be a presentation of the mechanisms that drive the evolution of the repository system. To determine the repository evolution, an initial state must also be determined, along with a description of how the system interacts with its surroundings. The initial state is described in the next chapter; in other words, the variables are assigned initial values.

5.2 Overview of the KBS-3 system

The repository design is based on the KBS-3 system with encapsulation of the fuel in corrosion-resistant canisters that are surrounded by a clay buffer and disposed of at a depth of approximately 500 metres in the Swedish crystalline bedrock. The canisters are deposited in a system of tunnels where the deposition holes have been bored in the floors of the tunnels.

In addition to a repository for spent nuclear fuel (SFL 2), a repository for other long-lived waste (SFL 3–5) will also be built. SFL 3–5 is similar to the final repository for radioactive operational waste (SFR) that is in operation today outside Forsmark. The siting of the repository for other long-lived waste has not yet been decided. A preliminary facility design and safety assessment for a repository for other long-lived waste has been prepared in parallel with SR 97 and is presented in a separate report /SKB, 1999/. The safety-related consequences of a possible co-siting are not investigated in SR 97.

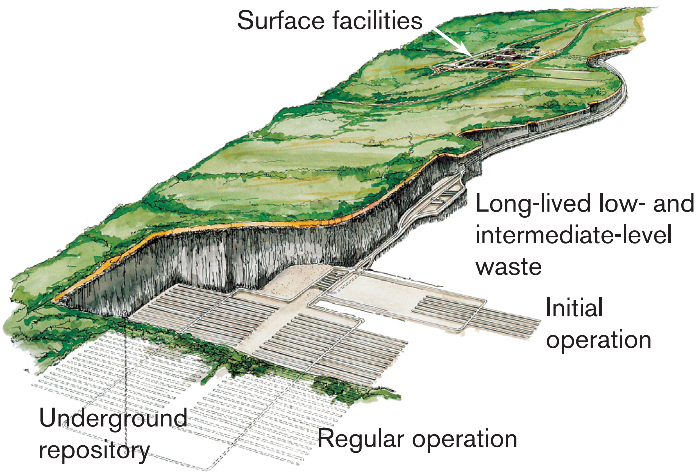

Figure 5-1. *Sketch of deep repository for spent nuclear fuel. The sketch also shows a possible location for a repository for other long-lived waste. This is not analyzed in SR 97.*

The facility design with rock caverns, tunnels, deposition positions etc. in the deep repository for spent fuel is based on the design presented in the KBS-3 report /SKBF/KBS, 1983/. The different parts of the deep repository are sketched in Figure 5-1.

The deep repository for spent fuel will be built in one or two levels at a depth of about 500 metres. It consists of parallel deposition tunnels with deposition holes bored in the bottom. The deposition tunnels are linked by tunnels for transport, communication and ventilation. The tunnels are connected to a central area underground. In SR 97 it is assumed that all tunnels are blasted using conventional technology.

The decay heat in the deposited fuel will lead to a heating of the repository. The positioning of the deposition tunnels, as well as the distance between the canister positions, is determined by the requirement that the temperature on the canister surface may not exceed 100°C.

5.3 Fuel

5.3.1 General

Fuel quantities

The total quantity of fuel obtained from the 12 Swedish nuclear reactors will depend on operating time, energy output and fuel burnup. At the beginning of 1998 approximately 4,000 tonnes of spent fuel have been generated /SKB, 1998/. With an operating time of 40 years for all reactors, the total quantity of spent fuel can be estimated at 9,500 tonnes /SKB, 1998/. The equivalent quantity for 25 years' operating time is 6,500 tonnes.

In SR 97 it is assumed that approximately 8,000 tonnes of fuel will be disposed of, see further section 6.5.3.

Fuel types

Several types of fuel will be emplaced in the repository. For an alternative with 25 years of reactor operation, the fuel quantity from boiling water reactors, BWR fuel, is estimated at 5,000 tonnes, while the quantity from pressurized water reactors, PWR fuel, is estimated at about 1,500 tonnes /SKB, 1998/. In addition, 23 tonnes of mixed-oxide fuel (MOX) fuel and 20 tonnes of fuel from the decommissioned heavy water reactor in Ågesta will be disposed of.

In SR 97 it is assumed for the sake of simplification in most subanalyses that all canisters contain BWR fuel of type SVEA 96 with a burnup of 38 MWd/tU.

PWR fuel differs marginally from BWR fuel when in comes to radionuclide content. Other aspects of importance in the safety assessment, for example the geometry of the fuel cladding tubes, are as a rule handled so pessimistically in analyses of radionuclide transport that differences between different fuel types are irrelevant. The difference between MOX fuel and uranium fuel is discussed in /Forsström, 1982/. The MOX fuel has a higher decay heat than uranium fuel, which means that less fuel can be emplaced in each canister.

Differences between different fuel types are more important for criticality assessments. BWR fuel of type SVEA-64 and PWR fuel of type FA17x17 are dealt with in SR 97, since these types are most unfavourable with regard to criticality.

Structure of the fuel assemblies

Nuclear fuel consists of cylindrical pellets of uranium dioxide. The pellets are 11 mm high and have a diameter of 8 mm. In SVEA 96 fuel, the pellets are stacked in approximately 4-metre-long cladding tubes of Zircaloy, a durable zirconium alloy. The tubes, or "cans", are sealed with welds and bundled together into fuel assemblies. Each assembly contains 96 cladding tubes. A fuel assembly also contains components of the nickel alloys Inconel and Incoloy, and of stainless steel.

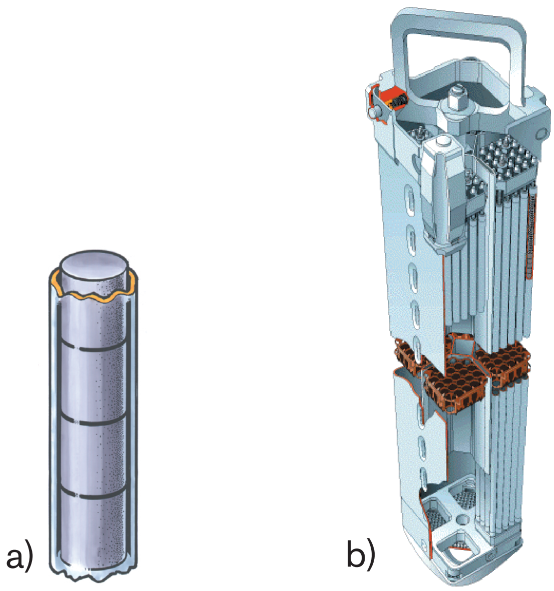

Figure 5-2.
a. Cylindrical fuel pellets in cladding tubes of Zircaloy. The pellets have a diameter of approximately one centimetre.
b. Fuel assembly of type SVEA 96. The assembly consists of 96 fuel tubes and has a height of approximately 4 metres.

Radionuclides

Radionuclides are formed during reactor operation by nuclear fission of uranium-235 and plutonium-239 in particular, and by neutron capture by nuclei in the metal parts of the fuel. The former are called fission products, the latter activation products. Moreover, uranium can form plutonium and other heavier elements by absorbing one or more neutrons. These and other elements (including uranium) are called actinides and decay to radioactive actinide daughters in several steps, finally forming stable isotopes of the metals lead or bismuth.

Most of the radionuclides lie embedded in the fuel matrix of uranium dioxide. A few fission products are relatively mobile in the fuel and may migrate to the surface of the fuel pellets during operation. The distribution of radionuclides in the fuel is discussed in detail in the Process Report.

5.3.2 Overview of variables

For the safety assessment, the fuel is described by means of a set of variables which together characterize the fuel in a suitable way for the assessment. The description applies not only to the fuel itself, but also the cavities in the canister, into which water can penetrate in the event of a defect in the copper canister. Crucial processes will then take place in the cavity, such as fuel dissolution and corrosion of the cast iron insert. The cavity could thus be included in either the fuel or the canister part of the system, and has been included in the fuel here.

The fuel is characterized with respect to radiation by the intensity of α, β, γ and neutron radiation and thermally by the temperature. Hydraulically, it is interesting to characterize the cavity if the copper canister should be damaged and water should enter. Hydraulically, the cavity is characterized by water flows and water pressures as well as by gas flows and gas pressures, which are jointly termed hydrovariables in the system description. Mechanically, the fuel is characterized by stresses in the materials, and chemically by the material composition of the fuel matrix and metal parts, as well as by the radionuclide inventory. If water enters the canister, water composition and gas composition also become relevant in the description. The variables are defined in Table 5-1.

5.3.3 Overview of processes

A number of processes will with time alter the state in the fuel and in the canister's cavity. Some take place in any circumstances, while others only occur if the isolation of the copper canister is breached and water enters the canister.

The radionuclides in the fuel will eventually be transformed into non-radioactive substances by means of radioactive decay. This process gives rise to α, β, γ and neutron radiation which, by interaction with the fuel and with surrounding materials, is attenuated and converted to thermal energy. The temperature in the fuel is changed by means of heat transport in the form of heat conduction and heat radiation, and heat is transferred to the surroundings. The temperature change will lead to some thermal expansion of the constituents of the fuel. In combination with the helium formation to which the α radiation gives rise, this can lead to mechanical failure of the cladding tubes in the fuel.

Table 5-1. Variables in fuel/cavity.

Geometry	Geometric dimensions of all components of the fuel assembly, such as fuel pellets and Zircaloy cladding. Also includes the detailed geometry, including cracking, of the fuel pellets.
Radiation intensity	Intensity of α, β, γ and neutron radiation as a function of time and space in the fuel assembly.
Temperature	Temperature as a function of time and space in the fuel assembly.
Hydrovariables	Flows and pressures of water and gas as a function of time and space in the cavities in the fuel and the canister.
Mechanical stresses	Mechanical stress as a function of time and space in the fuel assembly.
Radionuclide inventory	Occurrence of radionuclides as a function of time and space in the different parts of the fuel assembly. The distribution of the radionuclides in the pellets between matrix and surface is also described here.
Material composition	The materials of which the different components in the fuel assembly are composed, excluding radionuclides.
Water composition	Composition of water (including any radionuclides and dissolved gases) in the cavities in the fuel and canister.
Gas composition	Composition of gas (including any radionuclides) in the cavities in the fuel and canister.

In an intact canister, radiolysis of residual gases in the cavity will lead to the formation of small quantities of corrosive gases, which could contribute to stress corrosion cracking (SCC) of the cast iron insert.

If the copper canister is penetrated, water may be transported into the canister cavity, radically altering the chemical environment. Radiolysis of the water in the cavity will further alter the chemical environment. The water in the canister causes corrosion of cladding tubes and other metal parts in the fuel. If the cladding tubes' isolation should be breached initially or later by corrosion or mechanical stresses, the fuel will come into contact with water. This leads to dissolution of radionuclides that have been collected on the surface of the fuel matrix and dissolution or transformation of the fuel matrix with release of radionuclides. The radionuclides may either be dissolved in the water, rendering them accessible for transport, or precipitate in solid phases in the canister void. This is determined by the chemical speciation of radionuclides in the canister cavity. On dissolution of the fuel, microscopic particles (colloids) with radionuclides may also form.

Radionuclides dissolved in water can be transported with mobile water in the canister, advection, or by diffusion in stagnant water. Fuel colloids carrying radionuclides can be transported in the same way. Nuclides dissolved in water can be sorbed to the different materials in the canister. Certain nuclides can also be transported in the gas phase.

Finally, water can attenuate the energy of neutrons in the canister cavity. Low-energy neutrons can subsequently cause fission of certain nuclides in the fuel, releasing more neutrons. If conditions are unfavourable, criticality could be achieved, i.e. the process would become self-sustaining. The repository is designed so that criticality is avoided.

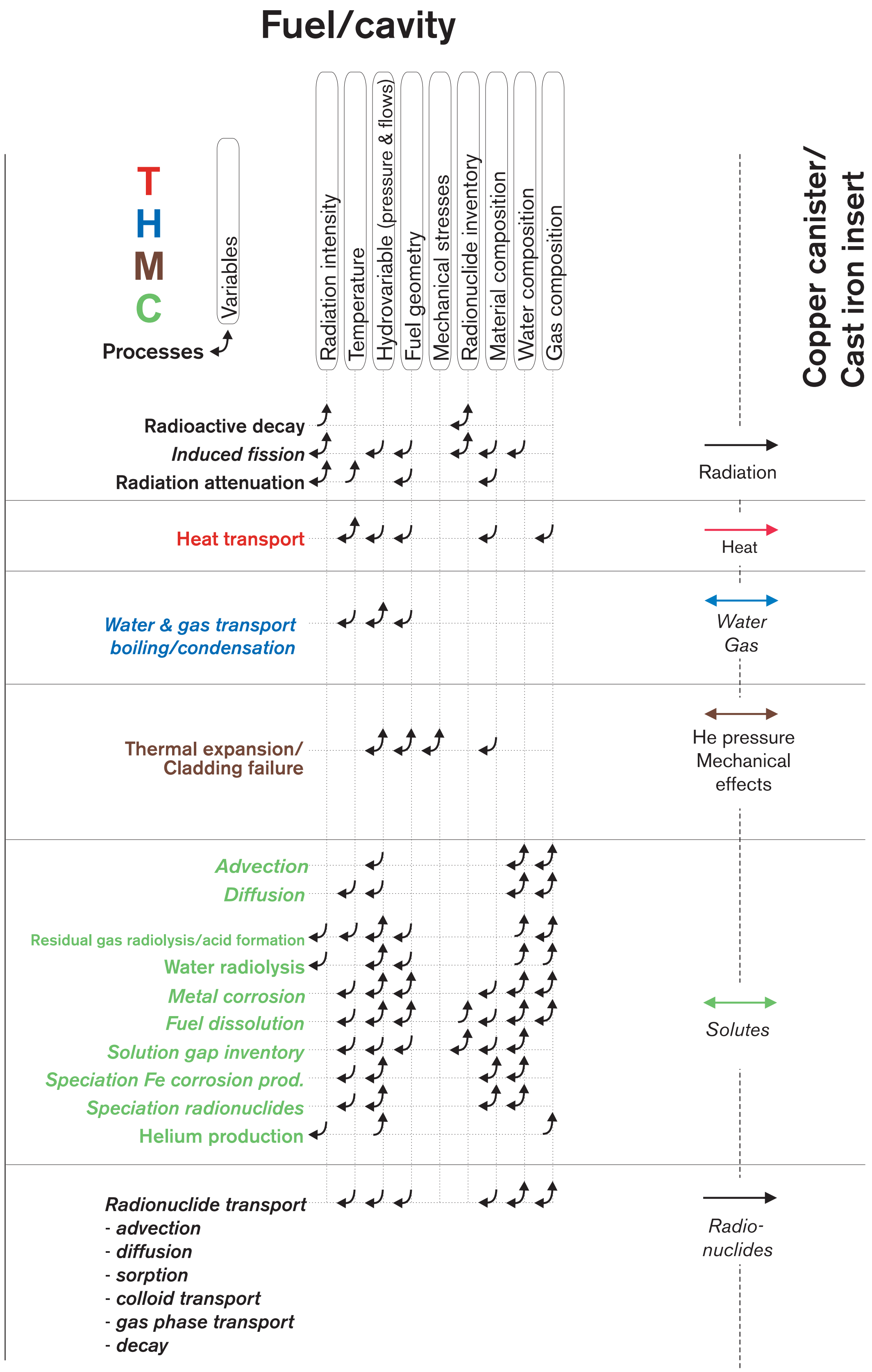

Figure 5-3. THMC diagram for fuel/cavity. Processes in italics only occur when the isolation of the copper canister is breached.

5.4 Cast iron insert/copper canister

5.4.1 General

The canister consists of an inner container of cast iron and a shell of copper, Figure 5-4. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment. The copper shell is 5 cm thick and the canister takes the form of an approximately 4.8 metre tall cylinder with a diameter of 1.05 metres.

The insert has channels where the fuel assemblies are placed and is available in two versions: one for 12 BWR assemblies and one for 4 PWR assemblies. The fuel channels are fabricated in the form of an array of square tubes. The walls and bottom of the inner container are then fabricated by casting spheroidal graphite iron around the channel array.

The copper canister is fabricated either of drawn seamless tubes or by welding together two tube halves of rolled plate. A bottom is attached by an electron beam weld in such a way that the weld can be examined by ultrasonic and radiographic inspection.

After fuel has been placed in the canister, the insert is closed with an O-ring-sealed lid which is fastened with a bolt. The copper shell's lid is then attached by an electron beam weld, and leaktightness is tested by ultrasonic and radiographic inspection.

The canister weighs a total of about 25 tonnes when filled with 12 BWR assemblies. A canister holds about two tonnes of fuel. It is assumed in SR 97 that approximately 8,000 tonnes of fuel will be disposed of, equivalent to around 4,000 canisters.

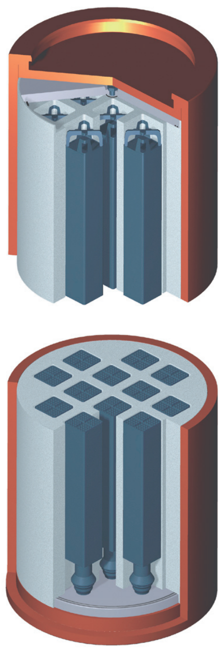

Figure 5-4. *Copper canister with cast iron insert.*

Table 5-2. Variables in copper canister/cast iron insert.

Geometry	Geometric dimensions for the canister components. This also includes a description of any fabrication defects in welds etc.
Radiation intensity	Intensity of α, β, γ and neutron radiation as a function of time and space in the canister components.
Temperature	Temperature as a function of time and space in the canister components.
Mechanical stresses	Mechanical stress as a function of time and space in the canister components.
Material composition	Material composition of the canister components.

5.4.2 Overview of variables

The subsystem cast iron insert/copper canister is described geometrically by the canister geometry, with respect to radiation by the radiation intensity (mainly γ and neutron radiation) and thermally by the temperature. Mechanical stresses and material compositions for insert and canister characterize the subsystem mechanically and chemically. The variables are defined in Table 5-2.

5.4.3 Overview of processes

Some of the radiation that reaches out into the canister is converted to thermal energy by radiation attenuation. Heat transport takes place by conduction inside the insert and the canister and to a large extent by radiation between these two parts.

Hydraulic processes can occur in the cavities that exist between canister and fuel and between cast iron insert and copper canister and are dealt with in the subsystem fuel/cavity.

Mechanically, the insert and the canister can be deformed by external loads and, in the event of canister damage, by mechanical pressure from products from corrosion of the cast iron insert. Furthermore, thermal expansion occurs, changing the cavity between insert and canister.

An important chemical process is external copper corrosion; stress corrosion cracking could also occur in both copper canister and cast iron insert. The materials could be changed by radiation effects. If water enters, corrosion of the cast iron insert accompanied by hydrogen gas generation and galvanic corrosion will occur.

Radionuclide transport in the canister cavity is dealt with in the subsystem fuel/cavity.

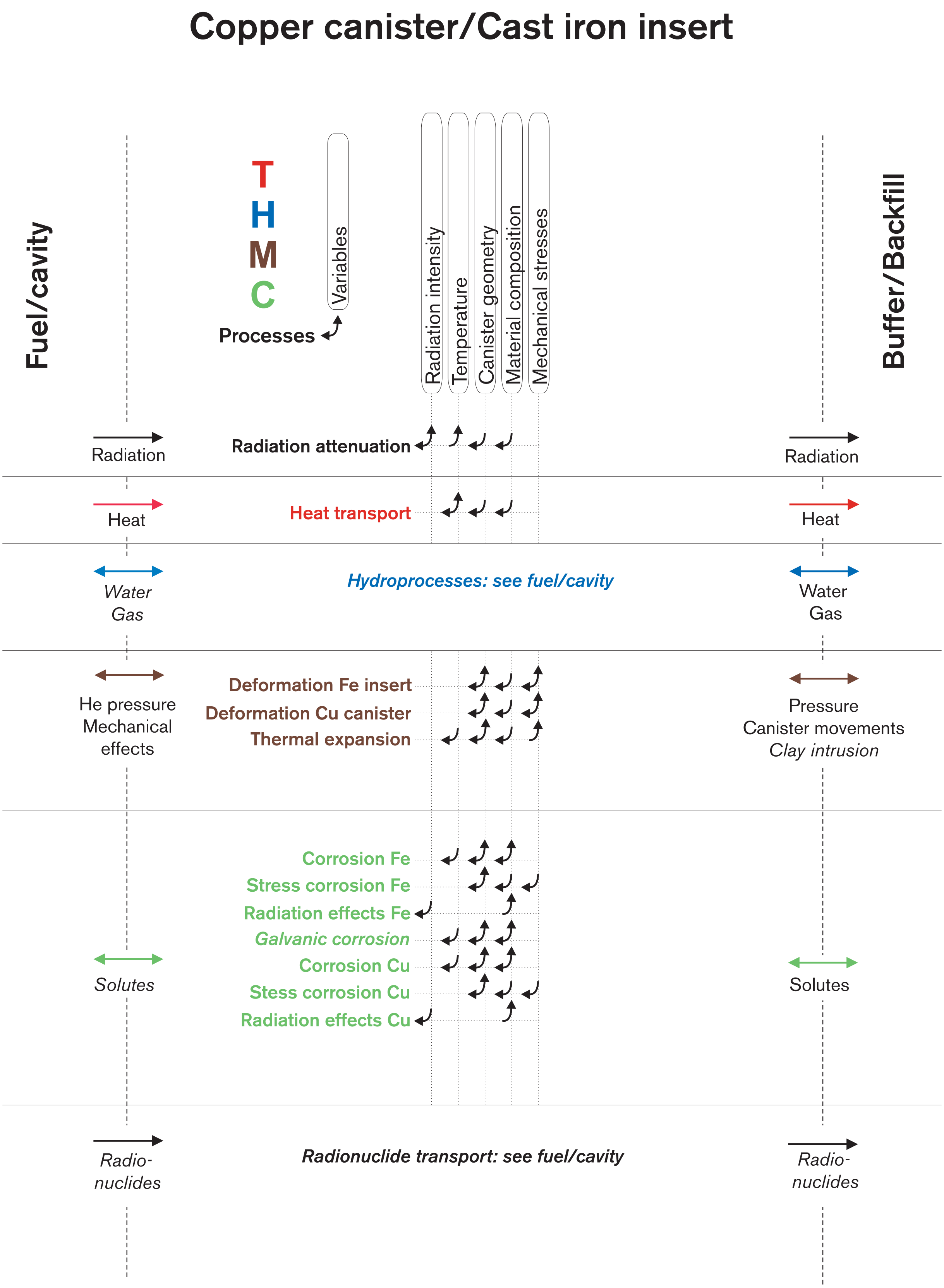

Figure 5-5. *THMC diagram for cast iron insert/copper canister. Processes in italics only occur when the isolation of the copper canister is breached.*

5.5 Buffer/backfill

5.5.1 General

In their deposition holes, the copper canisters will be surrounded by a buffer of bentonite clay, see Figure 5-6. On deposition, gaps are left for technical reasons between canister and buffer and between buffer and rock. The inner gap is filled with water and the outer with bentonite pellets.

After deposition, the tunnel above the deposition hole will be backfilled with a material that is adapted to the chemical conditions on the repository site.

Buffer material

The buffer consists of MX-80 bentonite, a natural clay from Wyoming or South Dakota in the USA. The designation MX-80 is a trade name and specifies a certain grade and particle size of dried and ground bentonite.

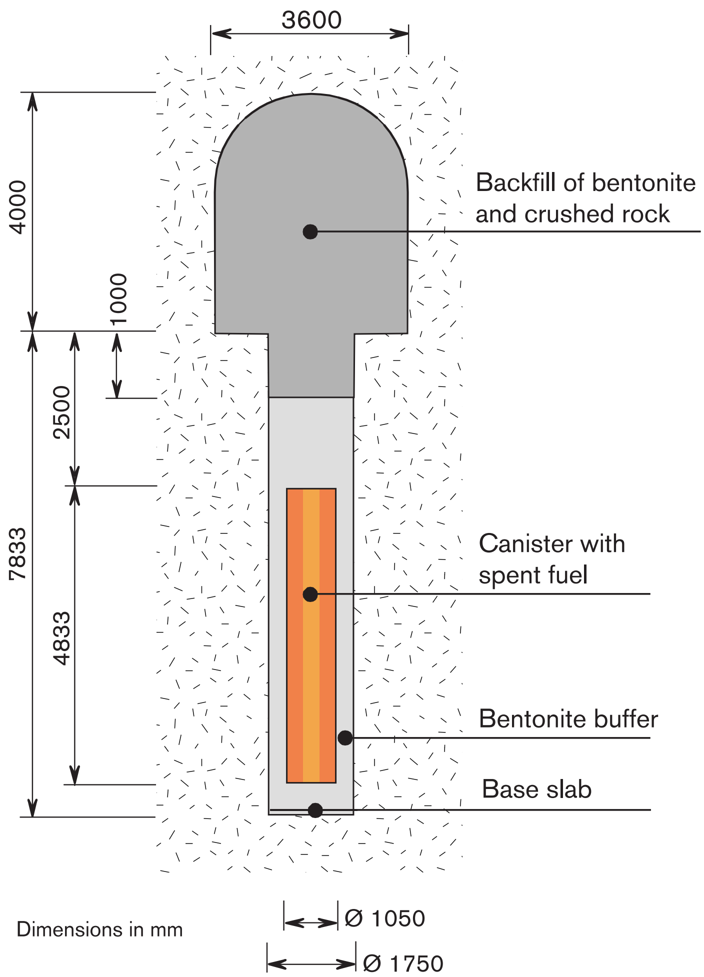

Figure 5-6. *Deposition hole with bentonite buffer and canister. The figure also shows the backfilled tunnel above the deposition hole.*

MX-80 bentonite consists mainly of the smectite mineral montmorillonite (65–80 percent), where the clay particles are smaller than 2 μm. Chemically, montmorillonite can be described as a polyelectrolyte, where exchangeable ions are associated with the surfaces of the negatively charged clay particles. A characteristic property of the clay is that it swells in contact with water. The exchangeable ions in MX-80 consist predominantly of sodium, and the material is therefore called sodium bentonite. Water-saturated buffer contains about 25 weight-percent water. The water molecules are absorbed in the material, and water transport takes place chiefly by diffusion.

MX-80 bentonite also contains the minerals quartz (about 15 percent) and feldspar (5–8 percent). Chemically important components in addition to the minerals are carbonates (e.g. calcite), sulphates, fluorides, sulphides (e.g. pyrite), iron(II) and organic matter.

After wetting, the bentonite will contain a pore water of a characteristic composition that depends on the composition of the bentonite and of the water used for wetting.

Backfill material

The backfill material consists of a mixture of bentonite clay and crushed rock. The proportions are adapted to the chemical conditions on the repository site so that the backfill will have the desired characteristics. Such site-specific adaptation has not been done in SR 97. Instead, a typical composition is used consisting of 15 weight-percent MX-80 bentonite clay and 85 weight-percent crushed rock.

5.5.2 Overview of variables

In the buffer/backfill subsystem, the buffer is bounded on the inside by the interface towards the canister, on the outside and bottom by the interfaces towards the deposition hole, and on the top by the interface towards the backfill. The backfill is constrained in space by backfilled tunnel systems and rock chambers. There are also plugs whose purpose is to seal the tunnel system hydraulically, but these have not been included in the description in SR 97.

The buffer as it is delimited by the variable buffer geometry is characterized thermally by its temperature and with respect to radiation by its radiation intensity, mainly γ and neutron radiation. Hydraulically, the buffer is characterized by its water content, and sometimes by gas concentrations and by water pressure, water flow, gas pressure and gas flow. The last four, which are mainly of interest in the phase when the buffer is being saturated with water, have collectively been named hydrovariables. Mechanically, the buffer is characterized by a swelling pressure.

The chemical state of the buffer is defined by its smectite content and its smectite composition, which is the composition of the actual clay mineral, including the ionic species associated to the surface, different impurity contents and a pore water composition.

The same set of variables is used for the backfill as for the buffer. The crushed rock, which comprises 85 percent of the backfill, is included in the variable impurity contents.

All variables are defined in Table 5-3.

Table 5-3. Variables in buffer/backfill.

Geometry	Geometric dimensions for buffer/backfill. A description of e.g. interfaces on the inside towards the canister and on the outside towards the geosphere.
Pore geometry	Pore geometry as a function of time and space in buffer and backfill. Often porosity is given, i.e. the fraction of the volume that is not occupied by solid material.
Radiation intensity	Intensity of (α, β,) γ and neutron radiation as a function of time and space in buffer (and backfill).
Temperature	Temperature as a function of time and space in buffer and backfill.
Smectite content	Smectite content as a function of time and space in buffer and backfill.
Water content	Water content as a function of time and space in buffer and backfill.
Gas contents	Gas contents (including any radionuclides) as a function of time and space in buffer and backfill.
Hydrovariables	Flows and pressures of water and gas as a function of time and space in buffer and backfill.
Swelling pressure	Swelling pressure as a function of time and space in buffer and backfill.
Smectite composition	Chemical composition of the smectite (including any radionuclides) in time and space in buffer and backfill. This variable also includes material sorbed to the smectite surface.
Pore water composition	Composition of the pore water (including any radionuclides and dissolved gases) in time and space in buffer and backfill.
Impurity levels	Levels of impurities in time and space in buffer and backfill. Impurities also include other minerals than smectite. In backfill, crushed rock is an inpurity.

5.5.3 Overview of processes

On emplacement, the buffer comes into contact with the hotter canister surface, the thermal energy is spread through the buffer by heat transport and the temperature increases. The γ and neutron radiation emitted by the canister decreases in intensity by radiation attenuation in the buffer.

A negative capillary pressure exists originally in the pores in the buffer, causing water to be transported in from the surrounding rock. After the buffer has been saturated with water, this water transport is very slow. Gas transport can occur during the saturation process, when water vapour can flow from the hotter parts of the buffer to condense in the outer, colder parts. Originally there is also air in the buffer, which can leave the buffer by dissolving in the pore water; gas dissolution. After water saturation, gas transport can occur if a canister is damaged, leading to hydrogen gas generation in the canister.

On absorbing water, the buffer and backfill swell and a swelling pressure is built up. The swelling pressure is different in the buffer and backfill, which therefore interact mechanically. Among other things, the swelling pressure causes any cracks that may form in the buffer to "self-heal". On heating, the pore water may expand due to thermal expansion.

The chemical evolution in buffer and backfill is determined by a number of transport and reaction processes. Solutes in the water may be transported by advection and diffusion. In the buffer, advection occurs almost exclusively during the water saturation process, after which diffusion dominates. By means of ion exchange/sorption, the original ions on the surfaces of the clay particles in the buffer may be replaced by other ionic species. Chemical smectite degradation may occur, e.g. in the form of illitization.

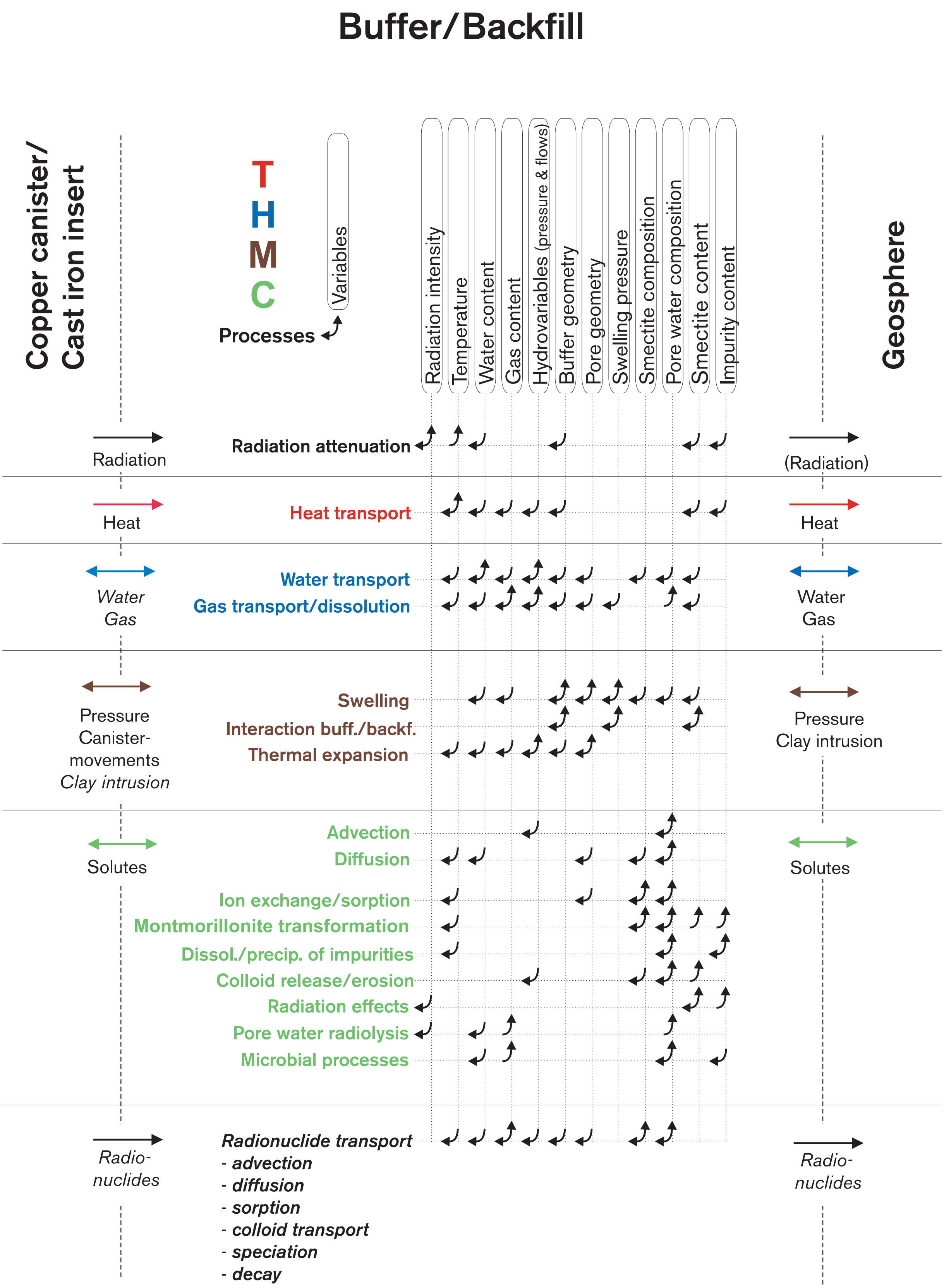

Figure 5-7. THMC diagram for buffer/backfill. Processes and interactions in italics only occur when the isolation of the copper canister is breached.

Impurities undergo various dissolution/precipitation reactions in the buffer. On swelling, the buffer penetrates out into the fractures in the surrounding rock, where it may form colloids which may be carried away by the groundwater, leading to gradual erosion of the buffer. The clay may be transformed by radiation effects and the pore water may be decomposed by radiolysis. Finally, microbial processes may occur in buffer/backfill.

After water saturation, radionuclide transport is expected to take place in the buffer exclusively by diffusion in the pores of the buffer, possibly also on the surfaces of the clay particles. Neither advection nor colloid transport are expected to occur in a saturated buffer. Radionuclides may be sorbed to the surfaces of the clay particles. A crucial factor for this is the chemical form of the radionuclide, which is determined by the chemical environment in the buffer via the process of speciation. Together with the transport conditions, the rate of radioactive decay determines to what extent radionuclides from a broken canister will decay before reaching the outer boundary of the buffer.

Virtually the same processes occur in the backfill as in the buffer, but often on a different scale. Furthermore, the crushed rock (defined as an impurity in the backfill) plays a somewhat different role than impurities in the buffer, for example by contributing to sorption.

5.6 Geosphere

5.6.1 General

The deep repository will be situated in crystalline rock of granitic composition. Granitic bedrock consists for the most part of quartz, feldspars (potassium feldspar), mica minerals (biotite and muscovite) and amphiboles (hornblende). In addition there are small quantities of accessory minerals, which may be of geochemical importance. Examples of accessory minerals are pyrite, chlorite, magnetite, calcite, dolomite, fluorite, apatite, anhydrite and different clay minerals.

The crystalline rock is also characterized by a system of fractures. The frequency, spatial distribution, size distribution, shape and orientation of the fractures are crucial in determining both hydraulic and mechanical properties in the rock. Fractures occur on all scales from microscopic fractures in the rock matrix to fracture zones, i.e. large zones of significantly elevated fracture frequency in relation to the surrounding rock. Fracture zones often constitute dominant flow paths for the groundwater, and their size is related to the size of the rock movements that can occur in the zone.

5.6.2 Overview of variables

The subsystem geosphere is bounded inwardly by the repository geometry, i.e. the interface between geosphere and buffer/backfill. Outwardly, the geosphere is bounded on top by the biosphere. In other directions, no clear boundary has been defined for that part of the geosphere that is included in the repository system and is thus described in detail. As a rule of thumb, detailed local analyses of e.g. groundwater flow and heat transport are carried out in a volume that extends from the repository to the surface and equally far, i.e. around 500 metres, in other directions as well. Those parts of the geosphere that lie outside this volume are called "distant geosphere" and are included in the surroundings. Where the boundary goes is allowed to vary as needed in different analyses.

The geosphere as it is delimited by the variable repository geometry/boundary is characterized by the mineralogical composition of the rock matrix, matrix minerals, the temperature of the rock and its mechanical rock stresses. The structure of the fracture system is expressed by the fracture geometry, and the mineralogical composition of the fracture surfaces and the fracture-filling minerals by the variable fracture minerals. Hydraulically, the geosphere is characterized by groundwater flows and gas flows in the fracture system. The groundwater composition is decisive for the chemical evolution of the geosphere, which is also influenced by gas composition and the presence of engineering and stray materials in the repository.

All variables are dependent on both time and space. A characteristic of the geosphere is that the majority of variables change very slowly in time, whereas the geosphere's spatial variation or heterogeneity is great. More exhaustive definitions of the different variables are given in conjunction with the description of the initial state in the geosphere, see section 6.5.

All variables are defined in Table 5-4.

Table 5-4. Variables in geosphere.

Repository geometry/ boundary	Geometric description of deposition holes, tunnels, ramps, plugs, rock supports etc. See also discussion of the boundary in section 4.2.1.
Temperature	Temperature as a function of time and space in the geosphere.
Groundwater flow	Groundwater flow as a function of time and space in the geosphere's fracture system.
Groundwater pressure	Groundwater pressure as a function of time and space in the geosphere's fracture system.
Gas flow	Gas flow as a function of time and space in the geosphere's fracture system.
Fracture geometry	Geosphere's cavities after construction of the repository. All cavities are included, from fracture zones to micropores in the matrix. Also included here is the excavation-disturbed zone (EDZ) and any other geometric changes in the fracture structure induced by construction.
Rock stresses	Rock stresses as a function of time and space in the geosphere.
Matrix minerals	Chemical composition of the rock matrix as a function of (time and) space, i.e. a description of the various minerals that occur and their extent.
Fracture-filling minerals	Chemical composition of the fracture surfaces as a function of (time and) space, i.e. a description of the various fracture-filling minerals that occur. Also the amount and composition of fracture-filling minerals in existing fractures.
Groundwater composition	The chemical composition of the groundwater as a function of time and space in the geosphere. This variable also includes quantities such as Eh and pH, as well as any radionulides and dissolved gases.
Gas composition	Chemical description of gases in geosphere cavities including any radionuclides.
Engineering and stray materials	Chemical composition and quantities of grouts, rock supports, plugs, etc.

5.6.3 Overview of processes

The geosphere will be heated up by heat transport from the fuel via the canister and the buffer.

The groundwater will be redistributed in the geosphere's fracture system by groundwater flow. Gas flow may also occur.

A mechanical state exists initially in the geosphere which is determined by the natural rock stresses and fracture systems on the repository site plus the changes to which construction of the repository has given rise.

The mechanical evolution is determined by how the geosphere responds to the different mechanical loads to which it is subjected. The loads may consist of the thermal expansion to which the heating of the repository leads, the pressure from swelling buffer/backfill, effects of earthquakes and the large-scale tectonic evolution. Changes in the geosphere may include fracturing, reactivation (sudden movements in existing fractures) or rock creep (slow redistributions in the rock). Movements in intact rock, i.e. compression/expansion of otherwise intact rock blocks, also occur.

The post-closure chemical evolution is determined by a number of transport and reaction processes. The predominant transport process in groundwater is advection, while diffusion plays a great role over short distances and in rock blocks where the water is immobile. In advection, solutes accompany the flowing water. The process leads to mixing of different types of water from different parts of the geosphere. Reactions occur between the groundwater and fracture surfaces in the form of dissolution/precipitation of fracture-filling minerals and, very slowly, between the groundwater and the minerals in the rock matrix. In the groundwater, microbial processes, degradation of inorganic materials from repository construction, colloid formation and gas formation take place. During a glaciation, methane ice formation and salt exclusion can also occur.

If radionuclides are released, they can be transported with the flowing groundwater, advection. Diffusion can also be important under stagnant conditions. An important aspect of this is matrix diffusion, i.e. radionuclides diffuse in the stagnant water in the microfractures in the rock and are thereby retained and transported more slowly than the flowing water. Sorption, where radionuclides adhere (sorb) to the surfaces of the fracture system and the rock matrix, is also crucial for radionuclide transport. Matrix diffusion and sorption are the two most important retention processes for radionuclides in the geosphere. Another factor that can be of importance for retention is sorption on colloidal particles and transport with them. The chemical environment in the water determines what speciation (chemical form) the radionuclides will have, which is crucial particularly for the sorption phenomena. Some nuclides can be transported in the gas phase. Finally, radioactive decay influences the groundwater's content of radionuclides and must therefore be included in the description of transport phenomena.

A detailed documentation of all processes can be found in the Process Report. The complete THMC diagram for the geosphere is shown in Figure 5-8.

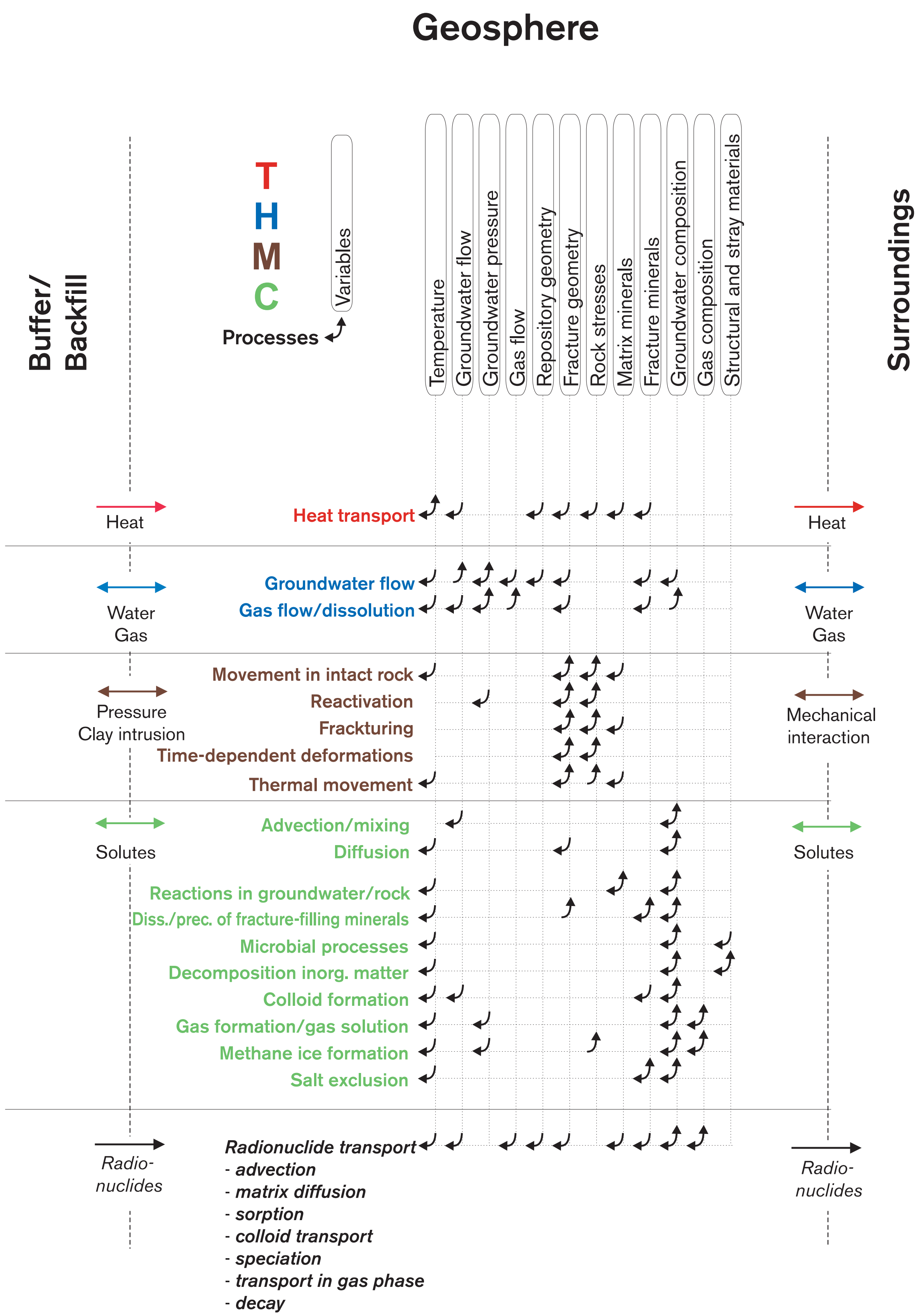

Figure 5-8. THMC diagram for the geosphere.

5.7 Safety criteria

According to section 4.1, the safety assessment describes the changes the repository system undergoes with time and what the safety-related consequences of these changes are. The general safety functions of a deep repository have to do with its isolating and retarding capacity. The acceptance criteria say that the risk of deleterious effects may not exceed 10^{-6} per year, see section 2.3.2.

An overall goal of the safety assessment is therefore to determine whether this criterion has been satisfied. The criterion is general and not tied to any special repository design. Based on the design of the KBS-3 system and its intended long-term functions, more specific "auxiliary criteria" can be formulated for long-term safety.

These auxiliary criteria do not determine safety directly, but serve as "guideposts along the road" in the actual safety assessment.

Canister

The first safety criterion is that the canister must remain intact for a very long time, i.e. its copper shell must not be breached.

Another criterion is that the temperature on the canister surface may not exceed 100ºC to avoid boiling on the canister surface /Werme, 1998/. Boiling could lead to enrichment of salts on the surface, which could in turn cause corrosion effects that are difficult to analyze. This criterion is thus of a different character than the isolation criterion: It is established to facilitate the assessment rather than because it is directly related to a safety function.

There are also design requirements on the canister, which are made to ensure that the isolation function will last for a long time. The design requirements are of assistance in selecting the canister's materials and dimensions, but are not used directly in the safety assessment. The safety assessment instead evaluates how well the canister design (which can sometimes withstand much more than the design requirements call for) copes with the stresses to which it is subjected in the different scenarios.

Buffer

For the buffer as well, there are various requirements which are used to determine suitable materials and dimensions. Few of these requirements are used in the actual safety assessment, where the performance of the chosen buffer is instead evaluated under the different conditions that will prevail in the scenarios.

The overall purpose of the buffer is to serve as a diffusion barrier between canister and rock. To fulfil this purpose, the buffer must have a low hydraulic conductivity and must be able to keep the canister centred in the deposition hole for a long time. It must also "self-heal" minor cracks in the clay that may arise e.g. initially during the saturation process. To ensure it performs as intended, the safety criteria for the buffer require that it must have over a long period of time

- a hydraulic conductivity of no more than 10^{-11} m/s,
- a sufficient density and
- a sufficient swelling pressure.

The hydraulic conductivity of the buffer is determined above all by density and smectite content. At the initial density of 2,000 kg/m^3, a smectite content of 10 percent is sufficient to meet the requirement, and at the initial smectite content, about 75 percent, a density of 1,500 kg/m^3 is sufficient /Pusch, 1995/.

Bearing capacity is mainly determined by density. There is no absolute requirement on density in this respect, but if the long-term changes are small compared with the permissible initial variation, 2,000 ± 100 kg/m^3, the density is sufficient to support the canister with good margin /Pusch, 1995/.

There is no absolute limit for the swelling pressure either, but even a swelling pressure of 1 MPa is fully sufficient to make the buffer mechanically "self-healing" /Pusch, 1995/. This value can be compared with the considerably higher swelling pressure the buffer attains after water saturation: 8 MPa. The swelling pressure is mainly determined by density, water content, smectite content and adsorbed ionic species, see the Process Report.

Backfill

The long-term safety criteria for the backfill say that it should have

- a hydraulic conductivity that does not significantly exceed the average conductivity of the surrounding rock, i.e. it should be around 10^{-10} m/s for typical conditions in Swedish bedrock.
- a swelling pressure of at least 0.1 MPa against the tunnel roof to support the rock around the tunnels /Process Report/.

The backfill should also prevent the buffer from protruding up into the tunnel when it swells. There are no absolute criteria for the properties of the backfill in this respect.

Geosphere

A criterion for the geosphere is that the groundwater at repository depth must be oxygen-free for a very long time. This is required to prevent oxygen corrosion of the copper shell, but also because it generally simplifies the analysis of the evolution of chemical conditions.

Otherwise it is difficult to formulate criteria for the geosphere that can be used directly in the safety assessment. The geosphere does indeed contribute to various safety functions: Its mechanical stability is important for isolation, the groundwater composition is of importance for corrosion processes and thereby isolation, etc. The problem as far as criteria are concerned is that many different measurable properties combine to contribute in a complex fashion to the functions of the geosphere. Criteria of the kinds formulated above for canister and buffer are therefore not used for the geosphere when the long-term evolution of the repository is studied in the safety assessment.

It can, however, be meaningful in site investigations to formulate both requirements and preferences on various aspects of the geosphere's initial state, i.e. on conditions which can be directly or indirectly observed in investigations of candidate repository sites.

The work of finding such geoscientific suitability indicators is under way. The work is guided by the long-term processes being studied in the safety assessment. The Process Report is therefore an important background document for the ongoing work, as is the safety assessment itself, which puts the different processes together into an integrated sequence, see further the discussion in the concluding chapter.

Safety criteria and variables

The safety criteria put limitations on a number of variables (geometry of the copper shell, temperature on the canister surface, swelling pressure and smectite content of the buffer, oxygen content of the groundwater) that should not be exceeded in the long term when the evolution of the repository is analyzed. Smectite content and swelling pressure will, for example, be affected by the fact that the evolution of chemical conditions leads to material changes in the buffer, the canister surface is heated due to the decay heat in the fuel, etc.

Concrete subtasks for the safety assessment will thereby be to check whether:

- the canister's copper shell is intact,
- the temperature on the canister surface is below 100°C,
- the hydraulic conductivity, density and swelling pressure of the buffer and the backfill lie within stipulated limits, and
- the groundwater at repository depth is oxygen-free.

The purpose of nearly all subanalyses can ultimately be traced in one way or another to one or more of these criteria.

The overall criterion is, however, always the limits on releases from the repository formulated by the safety and radiation protection authorities.

Time perspective

The length of time during which the repository must function is determined by how the radiotoxicity of the waste declines. The figure 100,000 years can, according to section 3.5, serve as a guideline, but there is no absolute limit as regards the time horizon for function. The same can be said about the time horizon for the above criteria, which has been formulated to permit verification of the proper function of the repository.

5.8 Completeness of system description

As observed in section 4.6.1, it can never be proved that the system description is complete, i.e. that it includes all processes and interrelationships relevant to the evolution of the repository. Confidence in the completeness of the system description must instead be subject to assessment.

Such an assessment can be based on both general arguments regarding the maturity of the natural sciences and specific arguments regarding the structure of the system description in a safety assessment.

Much of the understanding of the system rests on scientific foundations, which have in many cases remained unchanged for a long time. This is true, for example, of knowledge concerning radioactivity, thermodynamics and hydrodynamics (groundwater flow). To this basic body of knowledge can be added a couple of decades of research and development in technical and scientific fields which specifically concern the deep repository. Research is being conducted in many countries, and the international exchange of experience is an important part of the accumulation of knowledge and understanding of the evolution of the repository system.

Concrete administrative measures that can be adopted to achieve completeness in a system description are:

- Database management and other systematic documentation of all processes that have been identified as being important for the evolution of the repository.
- Comparisons with databases established by other organizations and in joint international projects.

In addition to a well-developed scientific knowledge base and advanced database management of relevant information, high competency of the experts who carry out system description and safety assessment is also required. Competency is required in both methodology and understanding of the function of the repository system.

Even though completeness cannot be proved, the consequences of an incomplete description can to some extent be illustrated. Assume, for example, that a process which rapidly degrades the copper canister was unidentified. The consequences of this can be illustrated by performing a calculation of radionuclide transport where the canister's isolation is assumed to be completely lost say 1,000 years after closure. Such analyses are reported as special cases in section 9.11.

The structure of the system description in SR 97, with choice of processes etc., was described briefly in section 4.2. It is SKB's judgement that all important processes in the evolution of the repository system are represented in the system description.

6 Initial state of the repository

(Includes site descriptions)

6.1 Introduction

The initial state of the different subsystems, broken down into the variables defined in Chapter 5, is described in this chapter. Uncertainties in the initial state are also discussed for each variable. Moreover, the description of the initial state of the geosphere constitutes the site description that is presented here in the main report. At the end of the section is a general description of the biosphere on each site.

The material for the geosphere description in particular is taken from the Repository System Report, which describes:

- the waste and the radionuclide inventory, based on the assumptions in PLAN 98,
- the engineered barriers and the conceptual design of the deep repository facility, and
- the three sites and the site-specific adaptation of the repository layout on each site.

The data on which the discussion of uncertainties is based is also taken from the Repository System Report for many variables. Uncertainties for the variables that directly comprise input data to calculations of radionuclide transport are discussed in the Data Report. These include e.g. the radionuclide inventory and the geometry of the copper canister (fabrication defects leading to loss of isolation).

SR 97 is carried out for the specific initial state that is described in this chapter. Many aspects of the repository's initial state can be influenced and controlled before an actual repository stands finished by a suitable design of barriers, quality in fabrication and operation, choice of site, choice of repository layout on the site, choice of positions for deposition holes, etc. Such an active approach ("Design as you go") during the process leading up to a finished repository is important for safety. This is made possible by referring to recurrent performance and safety assessments before making important decisions.

6.1.1 Time zero

The safety assessment is supposed to deal with post-closure safety, i.e. the era after the repository has been built, filled with spent fuel and closed. However, the repository is built gradually over several decades and it is therefore not possible to define an exact "time zero" for the repository as a whole.

The initial state is supposed to describe the point of departure for the various analyses that are carried out in coming chapters. Many analyses concern the sequence of events around individual deposition holes. All deposition holes will undergo roughly the same evolution from the time the canister and bentonite are deposited in them, regardless of where they are located in the repository and thereby regardless of when they enter into the progressively constructed repository. It is therefore natural to use the time of deposition as time zero for the description of the fuel, canister and buffer/backfill.

Other analyses concern the repository as a whole. Here there are great differences between different parts of the repository, owing to its progressive excavation. The problem with finding a time zero is, however, simplified by the fact that several key variables in the geosphere, such as fracture geometry, do not change appreciably during this construction period. For the geosphere it is not only the initial state immediately after construction that is important to describe. The natural state that prevailed before the repository was excavated is often of greater interest for post-closure safety, since conditions such as groundwater flow and groundwater composition can be expected to return to their natural states some time after the repository has been closed. This is discussed more thoroughly in the introduction to the geosphere section 6.5 below.

6.2 Fuel

6.2.1 Geometry

Initial value

Detailed dimensions for the reference fuel are found in the drawing and data sheet for the fuel /Appendix 1/. The Zircaloy cladding can act as a barrier to radionuclide transport if it is intact. This means that it is of interest to know how many fuel rods have defective cladding at deposition. Approximately 500 defective rods of a total of one million in interim storage in CLAB had been reported as of 1995 /SKB, 1995/.

Uncertainties

The geometric dimensions of the fuel assemblies are very well known. After encapsulation, the fuel will be exposed to high temperatures and the number of clad defects may then increase. These uncertainties are of importance for the analysis of radionuclide transport and are handled pessimistically there.

6.2.2 Radiation intensity

Initial value

Radiation intensity is reported in the form of dose rates. The dose rate from α and β radiation is totally dominant in the fuel pellets and in the fuel-clad gap. Outside the Zircaloy cladding, γ and neutron radiation dominate.

The dose rate on the surface of a fuel pellet has been estimated in Eriksen /1995/. Based on these results, the surface dose rate at the time of deposition, approximately 40 years after discharge from the reactor, can be estimated at about 700 Gy/h. The contribution from β radiation is approximately 15 percent. The estimate applies to PWR fuel with a burnup of 40 MWd/kg U.

At the same time, the γ and neutron dose rates at a distance of one metre from two tonnes of unshielded fuel (i.e. the contents of one canister) are 130,000 and 5 mGy/h, respectively (38 MWd/kg U BWR) /Hedin, 1997/.

Uncertainties

The radiation dose is dependent on the radioactivity, i.e. the radionuclide inventory, and the fuel's geometry. Both of these variables are well-known, and the dose rate can be calculated with sufficient accuracy for the needs of the safety assessment.

6.2.3 Temperature

Initial value

The temperature on the surface of the fuel at deposition is dependent on the decay heat, the thermal properties of the cast iron insert and copper canister, and the external cooling of the canister. The decay heat is well known, while the other factors are difficult to estimate before all steps in the handling sequence have been established. It is estimated that the temperature will be somewhere between 200 and 400°C /Bjurström and Bruce, 1997; Bjurström and Bruce, 1998/.

Uncertainties

As seen above, the uncertainties are great. However, the temperature lies in a range where the integrity of the fuel is not threatened, and the uncertainty in the temperature is therefore unimportant for post-closure safety.

6.2.4 Radionuclide inventory

Initial value

The inventory of radionuclides has been calculated by Håkansson /1999/. Table 6-1 shows the activity per tonne of fuel in the fuel assemblies 40 years after discharge from the reactor. A total of about 8,000 tonnes of fuel will be disposed of in the deep repository.

For some radionuclides, part of the inventory accumulates on the surface of the fuel pellets and thereby becomes more accessible for transport. Johnson and Tait /1997/ have estimated the size of this fraction. Table 6-2 shows these fractions and how large a portion of the inventory of the inventory is present in the structural parts of the fuel. This fraction is also relatively readily accessible for transport.

Uncertainties

The inventory of radionuclides in the fuel can be calculated with relatively high accuracy. The uncertainty is a few tens of percent or so and is related to the fuel's burnup, among other things. The surface fraction estimate is based on experimental data from Canadian CANDU fuel in particular. All the above data and uncertainties are discussed in the Data Report.

Table 6-1. Activity in reference fuel (SVEA 96. 38 MWd/kg U) 40 years after discharge from reactor /after Håkansson, 1999/.

Nuclide	Activity (Bq/t U) 40 years after discharge	Half-life*	Nuclide	Activity (Bq/t U) 40 years after discharge	Half-life*	Nuclide	Activity (Bq/t U) 40 years after discharge	Half-life*
Fission products			**Actinides and actinide daughters**				**Activation products**	
H-3	$2.1 \cdot 10^{12}$	12.33 years	Ra-226	$1.4 \cdot 10^{5}$	1,600 years	H-3	$1.1 \cdot 10^{12}$	12.33 years
Se-79	$2.8 \cdot 10^{9}$	$1.13 \cdot 10^{6}$ years	Th-229	$1.0 \cdot 10^{4}$	7,340 years	C-14	$5.0 \cdot 10^{10}$	5,730 years
Kr-85	$2.7 \cdot 10^{13}$	10.756 years	Th-230	$1.6 \cdot 10^{7}$	75,380 years	Cl-36	$5.5 \cdot 10^{8}$	301,000 years
Sr-90	$1.2 \cdot 10^{15}$	28.79 years	Th-234	$1.2 \cdot 10^{10}$	24.10 days	Fe-55	$9.3 \cdot 10^{9}$	2.73 years
Y-90	$1.2 \cdot 10^{15}$	64.10 hours	Pa-231	$1.8 \cdot 10^{6}$	32,760 years	Co-60	$8.9 \cdot 10^{11}$	5.2714 years
Zr-93	$5.0 \cdot 10^{10}$	$1.53 \cdot 10^{6}$ years	Pa-233	$1.5 \cdot 10^{10}$	26.967 days	Ni-59	$8.8 \cdot 10^{10}$	76,000 years
Nb-93m	$4.2 \cdot 10^{10}$	16.13 years	Pa-234m	$1.2 \cdot 10^{10}$	1.17 minutes	Ni-63	$9.3 \cdot 10^{12}$	100.1 years
Tc-99	$5.7 \cdot 10^{11}$	211,100 years	U-233	$3.1 \cdot 10^{6}$	159,200 years	Sr-90	$2.6 \cdot 10^{7}$	28.79 years
Ru-106	$2.7 \cdot 10^{4}$	373.59 days	U-234	$4.6 \cdot 10^{10}$	245,500 years	Y-90	$2.6 \cdot 10^{7}$	64.10 hours
Pd-107	$4.9 \cdot 10^{9}$	$6.5 \cdot 10^{6}$ years	U-235	$4.5 \cdot 10^{8}$	$7.038 \cdot 10^{8}$ years	Zr-93	$5.6 \cdot 10^{9}$	$1.53 \cdot 10^{6}$ years
Cd-113m	$1.7 \cdot 10^{11}$	14.1 years	U-236	$1.0 \cdot 10^{10}$	$2.342 \cdot 10^{7}$ years	Nb-93m	$2.3 \cdot 10^{10}$	16.13 years
Sn-121	$4.4 \cdot 10^{10}$	27.06 hours	U-237	$1.9 \cdot 10^{10}$	6.75 days	Nb-94	$2.9 \cdot 10^{9}$	20,300 years
Sn-121m	$5.7 \cdot 10^{10}$	55 years	U-238	$1.2 \cdot 10^{10}$	$4.468 \cdot 10^{9}$ years	Mo-93	$4.4 \cdot 10^{7}$	4,030 years
Sb-125	$1.1 \cdot 10^{10}$	2.7582 years	Np-237	$1.5 \cdot 10^{10}$	$2.144 \cdot 10^{6}$ years	Ag-108	$4.3 \cdot 10^{7}$	2.37 minutes
Te-125m	$2.7 \cdot 10^{9}$	57.40 days	Np-239	$1.2 \cdot 10^{12}$	2.3565 days	Ag-108m	$5.0 \cdot 10^{8}$	418 years
Sn-126	$2.3 \cdot 10^{10}$	100,000 years	Pu-238	$9.5 \cdot 10^{13}$	87.7 years	Cd-113m	$3.4 \cdot 10^{10}$	14.1 years
Sb-126m	$2.3 \cdot 10^{10}$	19.15 minutes	Pu-239	$9.5 \cdot 10^{12}$	24,110 years	Sn-121	$1.4 \cdot 10^{10}$	27.06 hours
I-129	$1.3 \cdot 10^{9}$	$1.57 \cdot 10^{7}$ years	Pu-240	$1.2 \cdot 10^{13}$	6,563 years	Sn-121m	$1.7 \cdot 10^{10}$	55 years
Cs-134	$9.1 \cdot 10^{9}$	2.0648 years	Pu-241	$7.7 \cdot 10^{14}$	14.35 years	Sb-125	$1.2 \cdot 0^{9}$	2.7582 years
Cs-135	$2.1 \cdot 10^{10}$	$2.3 \cdot 10^{6}$ years	Pu-242	$1.0 \cdot 10^{11}$	373,300 years	Te-125m	$3.0 \cdot 10^{8}$	57.40 days
Cs-137	$1.8 \cdot 10^{15}$	30.07 years	Am-241	$1.5 \cdot 10^{14}$	432.2 years	Eu-154	$3.2 \cdot 10^{11}$	8.593 years
Ba-137m	$1.7 \cdot 10^{15}$	2.552 minutes	Am-242m	$4.5 \cdot 10^{11}$	141 years	Eu-155	$1.3 \cdot 10^{10}$	4.7611 years
Pm-146	$9.8 \cdot 10^{8}$	5.53 years	Am-242	$4.5 \cdot 10^{11}$	16.02 hours	Ho-166m	$7.5 \cdot 10^{7}$	1,200 years
Pm-147	$1.5 \cdot 10^{11}$	2.6234 years	Am-243	$1.2 \cdot 10^{12}$	7,370 years	Total	$1.2 \cdot 10^{13}$	
Sm-151	$9.4 \cdot 10^{12}$	90 years	Cm-242	$3.7 \cdot 10^{11}$	162.8 days			
Eu-152	$3.3 \cdot 10^{10}$	13.537 years	Cm-243	$4.4 \cdot 10^{11}$	29.1 years			
Eu-154	$1.8 \cdot 10^{13}$	8.593 years	Cm-244	$2.8 \cdot 10^{13}$	18.10 years			
Eu-155	$7.6 \cdot 10^{11}$	4.7611 years	Cm245	$9.4 \cdot 10^{9}$	8,500 years			
Total	$6.0 \cdot 10^{15}$		Cm-246	$2.9 \cdot 10^{9}$	4,730 years			
			Total	$1.1 \cdot 10^{15}$				

* Karlsruher Nuklidkarte, 5th ed.

Table 6-2. Fraction of inventory that is immediately accessible (IRF = Instant Release Fraction) according to the Data Report /after Johnson and Tait, 1997/.

Nuclide	IRF (%) reasonable value, only fuel	IRF (%) reasonable value, including structural parts	IRF (%) pessimistic estimate
C-14	5	15	55
Cl-36	6	6	12
Co-60	–	–	–
Ni-59	–	100	100
Ni-63	–	100	100
Se-79	3	3	6
Kr-85	2	2	4
Sr-90	0.25	0.25	1
Zr-93	–	–	–
Nb-94	–	100	100
Tc-99	0.2	0.2	1
Pd-107	0.2	0.2	1
Ag-108m	3	100	100
Cd-113m	3	3	6
Sn-126	2	2	4
I-129	3	3	6
Cs-135	3	3	6
Cs-137	3	3	6
Sm-151	–	–	–
Eu-154	–	–	–
Ho-166m	–	–	–
Aktinider	–	–	–

6.2.5 Material composition

Initial value

The composition of the fuel assemblies is given in detail in Appendix 1. The radionuclide inventory in the structural parts before and after operation can be found in Håkansson /1999/, see the section above.

Uncertainties

The uncertainties in material composition are small, partly because the quality requirements in the fabrication of fuel assemblies are very strict.

6.2.6 Water composition

Initial value

The temperature and pressure in the cavities in the fuel and canister at deposition are such that water occurs in vapour form, see gas composition below.

Uncertainties

Not applicable.

6.2.7 Gas composition

Initial value

Fuel-clad gap: The fuel rods are filled with helium to a pressure of 0.4 MPa in fabrication. There are also fission gases from operation, of which mainly Kr-85 is left at the time of deposition.

Canister cavity: The canister will be sealed at atmospheric pressure (dry air) or under vacuum, which means that the pressure in the canister cavity may be a couple of atmospheres if the initial temperature is as high as 400ºC. Water vapour: The maximum permissible quantity of water in a canister is 50 grams. This value is equivalent to the void in a fuel rod and thus presumes that a Zircaloy cladding tube is defective during operation or interim storage.

Uncertainties

The uncertainties in pressure stem mainly from the uncertainties in temperature. Possible variations are of no importance for post-closure safety.

6.2.8 Hydrovariables

Initial value

Water pressures, water flows and gas flows are not relevant to describe initially. The gas pressure is discussed in section 6.2.7.

Uncertainties

Not applicable.

6.2.9 Mechanical stresses

Initial value, uncertainties

The fuel pellets have inherent stresses caused by grain growth etc. as a consequence of nuclear fissions and irradiation. The internal structure of the pellets is changed during irradiation depending on temperature and burnup. Fuel rods and structural elements have inherent stresses due to pressure from fission gases and gas filling. These stresses vary with the make and burnup of the fuel. The stress distribution in the assemblies is affected in an unpredictable manner by irradiation in the reactor due to the fact that irradiation sometimes causes growth/swelling of the structural materials and due to the fact that stress relaxation varies depending on local temporal variations in temperature.

This affects the surface of the fuel pellets, which is of importance for the rate at which radionuclides can be released if the fuel comes into contact with water. Data for the safety assessment are based on surface determinations of spent fuel that has been affected by the above-mentioned processes and conditions.

6.3 Cast iron insert/copper canister

6.3.1 Geometry

Initial value

The geometry of the canister is shown in Figure 6-1.

Uncertainties

Uncertainties in the initial geometry of the canister primarily concern canister integrity. The canisters will be fabricated, sealed and inspected with methods that guarantee that no more than 0.1 percent of the finished canisters contain defects that are greater than what is permitted by the acceptance criteria for nondestructive testing. This is a level that can be achieved with available testing methods /Werme, 1998/. The safety assessment therefore assumes that no more than one canister in a thousand has a defect of the types described in Werme /1998/, for example a non-penetrating cavity in the lid weld.

The probability of a defect is greatest in the lid weld, since the opportunities for inspection and testing are much greater for the bottom weld and the longitudinal weld (if the canister is made with one). In SR 97, it is therefore assumed that any defect in the canister is in the lid.

Initial canister damage is discussed more thoroughly in the canister defect scenario, Chapter 9.

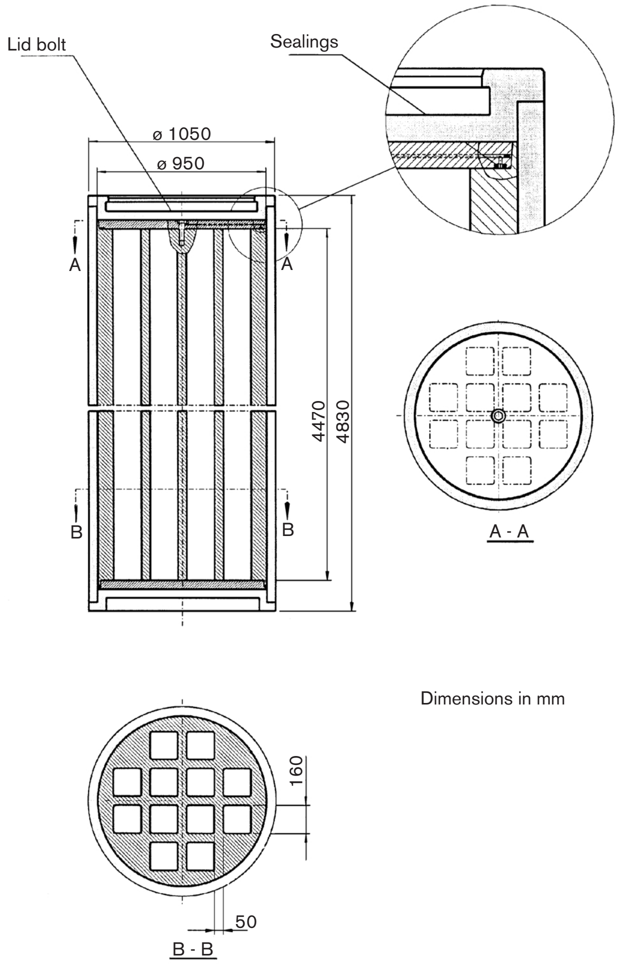

Figure 6-1. Design of copper canister and cast iron insert in BWR version.

6.3.2 Radiation intensity

Initial value

The dose rate caused by γ and neutron radiation outside the canister has been calculated by Håkansson /1996/. A canister with 40-year-old fuel emits γ and neutron dose rates of 350 and 20–40 mGy/h, respectively.

Uncertainties

Lundgren /1997/ compares different calculations of radiation doses around the canister. The values vary between 100 and 500 mGy/h for γ radiation at different positions on the canister surface, due among other things to the fact that the insert is not cylindrically symmetrical.

The γ dose rate outside the canister is of importance for radiolytic disintegration of water and for nitric acid formation from entrapped air before saturation of the buffer, see Chapter 8. The canister design criteria require that the γ dose rate not exceed 1 Gy/h in order to minimize the importance of the processes. The whole range of values given above is thereby within the limit.

6.3.3 Temperature

Initial value

The temperature of the canister surface at deposition is estimated to be around 90ºC.

Uncertainties

The surface temperature is dependent on the handling sequence at deposition (cooling) and the inventory of the fuel assemblies placed in the canister. The handling sequence has not been finally determined.

6.3.4 Material composition

Initial value

The insert consists of spheroidal graphite iron SS0717-00, and the copper shell of ASTM USN C10100 with addition of 50 ppm phosphorus. The surfaces of the insert and the shell are rough-machined.

Uncertainties

The properties of the metal surfaces are of great importance for heat transfer in the canister and between canister and buffer. These properties are dependent on the machining results and the environment in which the empty canister parts have been stored. This makes for high uncertainty in the emissivity of the surfaces.

6.3.5 Mechanical stresses

Initial value

Residual stresses remain in the lid weld after the canister is sealed. Attempts to determine the size of these stresses have been made both experimentally /Leggatt, 1995/ and by means of modelling /Lindgren et al, 1998/. The modelling showed that immediately after welding (20 seconds) the annual tensile stresses in particular may be high, up to 100 MPa, but they gradually relax and have fallen to about 50 MPa after a week. The tensile stresses will then gradually turn into compressive stresses when the copper shell comes into contact with the insert and the process stops after about three years /Lindgren et al, 1998/.

The tensile stresses that remain after a very long time are low and are judged not to be of any importance for canister life.

Uncertainties

The measured and the calculated residual stresses are in relatively good agreement. The greatest residual stresses immediately after welding are estimated to be in the range 50–100 MPa.

6.4 Buffer/backfill

6.4.1 Buffer geometry

Initial value

The dimensions of the buffer and backfill are dependent on the dimensions of tunnels and deposition holes. All geometric dimensions for buffer and backfill, as well as for initial gaps between canister-buffer and buffer-rock, can be found in Bäckblom /1996/, see also Figure 5-6.

Uncertainties

Buffer: Tolerances for dimensions, straightness and gaps are given in Bäckblom /1996/. Any rock breakouts in the deposition holes will be filled with bentonite pellets.

Backfill: The backfill is adapted to the tunnels, which are in turn adapted to the site.

6.4.2 Pore geometry (porosity)

Initial value, uncertainties

Buffer: According to Bäckblom /1996/, the final density is 2.00 ± 0.05 g/cm^3 and the dry density is 1.59 ± 0.03 g/cm^3. This gives a porosity of 41 percent. The uncertainties in density are correlated, so the uncertainty in porosity should be ± 2 percent.

Backfill: See above for the bentonite component.

6.4.3 Radiation intensity

Initial value

Lundgren /1997/ calculates the initial dose rate on the canister surface and on the outside of the buffer. The γ dose rate at the canister surface is 100–500 mGy/h (section 6.3.2). The dose rate on the outside of the buffer is approximately 2 mGy/h.

The dose rate in the backfill has not been calculated, since it is considerably lower than on the outside of the buffer and is of no importance in the safety assessment.

Uncertainties

Buffer: The dose rate on the outside of the buffer has diminished by a factor of 200 and varies in a similar manner as on the inside, see section 6.3.2.

6.4.4 Temperature

Initial value

Buffer and backfill are at ambient temperature at deposition. This varies with repository site and disposal depth and is approximately 10–15°C.

Uncertainties

The temperature is dependent to some extent on the handling sequence, where the buffer blocks have been stored, the heat from the deposition machine, etc. An uncertainty of around 5°C is reasonable. This is of no importance for the thermal evolution in the repository.

6.4.5 Smectite content

Initial value

Buffer: The smectite content in the buffer at deposition is approximately 75 percent.

Backfill: 15 percent of the backfill consists of bentonite with the same smectite content as the buffer.

Uncertainties

Buffer: MX-80 is a commercial product with a given composition. In SR 97, the smectite content requirement is assumed to be 75 percent. The delivered product will be quality-tested before being taken to the repository.

Backfill: See above.

6.4.6 Water content

Initial value

Buffer: The compacted bentonite blocks have an initial degree of saturation of 85 percent, while the pellets in the buffer-rock gaps have 50 percent. The buffer-canister and buffer-rock gaps are filled with water.

Backfill: The backfill material has an initial degree of saturation of 65 percent.

Uncertainties

The values given here are tolerances in the repository's specification.

Buffer: ± 5 percent in bentonite blocks, ± 15 percent in pellets

Backfill: ± 10 percent

6.4.7 Gas contents

Initial value

Buffer: The bentonite blocks have a degree of saturation of 85 percent, which means that 85 percent of the pore volume is filled with water and the remainder with air. The outer gap is filled with bentonite pellets and water and the inner with water. The air in a deposition hole occupies approximately 6 percent of the volume.

Backfill: The porosity in the backfill is 30 percent and the degree of saturation 65 percent, which means that the air in the tunnel system initially occupies about 10 percent of the volume.

Uncertainties

The uncertainties in gas contents are not important for post-closure safety.

6.4.8 Hydrovariables

The hydrovariables are water flow, water pressure, gas flow and gas pressure. Initially it is relevant to describe gas and water pressures. Flows do not occur initially in buffer/backfill.

Initial value

Buffer: At emplacement of canister and buffer, the deposition holes will be kept drained and the repository will be open to atmospheric pressure. This gives a gas pressure (air) of 1 atm (approx. 0.1 MPa) and a water pressure of 0–0.1 MPa.

Backfill: See buffer

Uncertainties

Buffer: Insignificant

Backfill: Insignificant

6.4.9 Swelling pressure

Initial value

The swelling pressure develops as the buffer/backfill approaches full water saturation. Initially there is no swelling pressure.

Uncertainties

Not applicable.

6.4.10 Smectite composition

Initial value

Buffer: In SR 97 the buffer is assumed to consist of MX-80 bentonite. It consists of approximately 75 percent Na-montmorillonite. Na-montmorillonite in MX-80 bentonite has the mineral formula:

$$(Si_{3.96}Al_{0.04})(Al_{1,55}Fe^{3+}_{0.20}Fe^{2+}_{0.01}Mg_{0.24})O_{10}(OH)_2\,Na_{0.30}$$

and has a cation exchange capacity of 73 meq/100 g with 85 percent Na and the remainder Ca and Mg /Müller-Vonmoos and Kahr, 1983/.

Backfill: The clay fraction (15 weight-percent) has the same composition as the buffer.

Uncertainties

MX-80 is a commercial product with specified requirements on, among other things, swelling capacity and ion exchange capacity. The uncertainties in the composition of the smectite are therefore small and are judged to be of no importance for safety.

6.4.11 Pore water composition

Initial value

Buffer: At delivery the water content is 12 percent maximum, according to the product specification. The water has a composition that is determined by the water composition on the site where the material was originally quarried. The water is also in or near equilibrium with the minerals included in the buffer. There are, however, no relevant measurements of the composition of the water in unsaturated bentonite. The raw material is dried and ground and distilled water is then added before compaction to achieve a water ratio of 17 percent, which is equivalent to a degree of saturation of 85 percent after compaction.

Backfill: The water in the backfill is a blend of water from the crushed rock, the bentonite's original water and water added at deposition.

Uncertainties

Buffer: Variations are due to the variation in the bentonite material. Since the material is relatively homogeneous, the variations are expected to be small.

Backfill: See above. Added to this are variations in the site-specific water in the crushed rock and in the water added at deposition.

6.4.12 Impurity contents

Initial value

Buffer: The most important impurities in MX-80 bentonite are given in Table 6-3. The bentonite can also be contaminated during the handling sequence. A compilation of possible impurities is found in Sjöblom /1998/.

Backfill: The natural impurities in the bentonite are of subordinate importance in the backfill, since it consists of 85 percent crushed rock, which in turn consists of minerals similar to the impurities in the bentonite. See further the mineralogical description of the geosphere.

Moreover, materials used during the excavation of the repository and at deposition may have been left behind in the deposition tunnels. Such materials may include tools, packaging and spilled organic liquids.

Uncertainties

Buffer: Bentonite is a naturally occurring material with natural variations in composition. MX-80 is a commercial product that is blended to meet given specifications. The uncertainties in impurity contents are therefore expected to be small and of no importance for the function of the buffer.

There is a compilation in Sjöblom /1998/ of maximum quantities of the impurities that might conceivably get into the bentonite during the handling steps. The important impurities are humus from quarrying, soot from drying and lubricants from compaction and transportation. The amounts of organic substances that could get into the bentonite during handling are orders of magnitude below the natural content, even assuming extreme events.

Backfill: See above for the bentonite component.

Table 6-3. Impurities in MX-80 bentonite /Müller-Vonmoos and Kahr 1983/.

Component	Content (weight-percent)
Carbonate (calcite)	1.4
Quartz	15
Pyrite	0.3
Non-swelling clay minerals	1.4
Kaolin	<1
Feldspar	5–8
Humic substances	0.04–0.4
Others	2

6.5 Geosphere

6.5.1 Time zero for the geosphere description

The description of the initial state is more complicated for the geosphere than for other repository sections. The description of the initial state must be based on interpretations of observations at the sites, and not on drawings and material specifications, as is the case for fuel, canister and buffer/backfill. The strong heterogeneity in the geosphere contributes further to these difficulties, since it is not possible to observe the entire geosphere directly. The state and properties in areas situated between actual measurement areas (ordinarily boreholes) can only be estimated by means of interpolation. The forecasts are based on more or less well-founded assumptions concerning the structure of the rock.

Furthermore, for several of the variables it is also of interest to know not just the initial state, i.e. that when the repository was just built, but also the natural state that prevailed before the facility was begun.

The starting point for the analysis is the situation that prevails when the repository has just been built and closed. For the geosphere, this situation is a disturbance of the state that prevailed before the repository was built. The hydraulic situation, i.e. groundwater flow and groundwater pressure, is in particular affected by the drainage. The hydrogeochemical situation is also influenced by the altered groundwater flow, as a result of which water of another composition may flow towards the repository. Chemical conditions are also influenced by the fact that the repository is kept open and various materials are introduced. The magnitude of this influence depends on several factors, for example how the repository was built and how long the repository is drained. Judging how the repository influences the state of the geosphere comprises a part of the analysis in the base scenario. In certain cases, e.g. regarding the thermal evolution, quantitative calculations are needed. In other cases, e.g. regarding groundwater flow, assessments are made of how and when the state reverts to the situation that prevailed prior to repository construction.

The groundwater flow situation is also complicated by the fact that a modelling is required to determine the initial state from the data that are obtained from a site investigation. Other variables, such as temperature, are directly observable.

Therefore, only a brief, qualitative account of the initial state is given here for the hydraulic variables groundwater flow, groundwater pressure and gas flow. How this state can be expected to revert to the naturally prevailing conditions is then described in the base scenario. In the case of groundwater flow and pressure, the base scenario also shows how modelling of the natural situation has been carried out. More detailed, local model studies are described in the canister defect scenario.

For the chemical variables groundwater composition (and gas composition), the undisturbed conditions that were measured in the field prior to construction are described. The possible impact of construction on these variables is also discussed.

Other variables such as rock stresses and by definition repository geometry and engineering and stray materials are permanently altered by construction. It is this altered state that is of interest to the further analysis and is also described below.

Remaining variables are moderately affected by construction: temperature, fracture geometry, matrix minerals and fracture minerals.

6.5.2 General about the sites in the safety assessment

Three hypothetical repository sites – Aberg, Beberg and Ceberg – are analyzed in SR 97 to illustrate actual conditions in Swedish crystalline bedrock. Data are taken from Äspö in Småland (southern Sweden), Finnsjön in Uppland (central Sweden) and Gideå in Ångermanland (northern Sweden), respectively, see Figure 6-2. The sites represent three areas in stable geological settings. All three sites are relatively near the coast, Äspö is an offshore island.

The three sites have been investigated by different experts on different occasions over a twenty-year period in studies of somewhat differing purpose and scope. There are therefore differences between the terminology used on the different sites (for example to describe fracture zones), what has been investigated and how the results have been analyzed and presented. The original nomenclature and mode of presentation has largely been retained in SR 97, which means that terms and formats of maps differ in some respects between the three sites.

The quantity of material is biggest for Äspö and smallest for Gideå. It is described in detail in the Repository System Report and summarized in this section.

At Äspö, SKB built a Hard Rock Laboratory (the Äspö HRL) between 1986 and 1995 for the purpose of exploring the bedrock and carrying out demonstration exercises at repository depth in a previously undisturbed area. A large quantity of data were collected before and during construction of the underground facility. The laboratory is used today for research purposes and data on the rock are gathered continuously from various research projects in the laboratory. Only data from the pre-investigations and from the construction phase are used in SR 97, however.

Finnsjön was first investigated during the period 1977–1978 within the framework of the KBS project. During 1985–1991, studies were conducted of a low-dipping fracture zone to obtain detailed information on the importance of flat zones for groundwater transport and groundwater-borne solutes.

At Gideå, investigations were conducted during the period 1981–1983 as a basis for the KBS-3 safety assessment. The investigations have been supplemented in SR 97 with, among other things, a comprehensive review or original data where new models have been devised for structural geology and geohydrology in the rock.

The Geological Survey of Sweden recently presented geological overviews of the counties in which the sites are situated. Due to limited time, the results of these overviews have not been incorporated in SR 97.

The bedrock at Äspö is mineralogically heterogeneous and has a relatively high content of fracture zones and fractures. Its permeability is relatively high in both fracture zones and rock mass. The groundwater is saline at repository depth. Its salinity is higher than the surrounding sea, which suggests the presence of connate seawater. The coastal location with ongoing land uplift is leading to a slow washing-out of the saline groundwater by a non-saline groundwater.

Finnsjön is a mineralogically homogeneous area with a medium-high content of fracture zones and fractures. Its permeability is relatively high in both fracture zones and rock mass. What particularly distinguishes Finnsjön is the flat fracture zone in the northern block. It is highly permeable and has a high natural flow in its upper portion. In the lower portion of the zone, flow measurement and groundwater composition indicate very low groundwater flows. The groundwater is saline with some connate seawater.

In the long term, the coastal location, with ongoing land uplift, will lead to replacement of the saline groundwater by a non-saline water.

Gideå is also a fairly homogeneous area mineralogically speaking, with the exception of frequently occurring vertical dolerite dykes. The frequency of fracture zones is low, even at repository depth. Permeability in fracture zones and rock mass is relatively low.

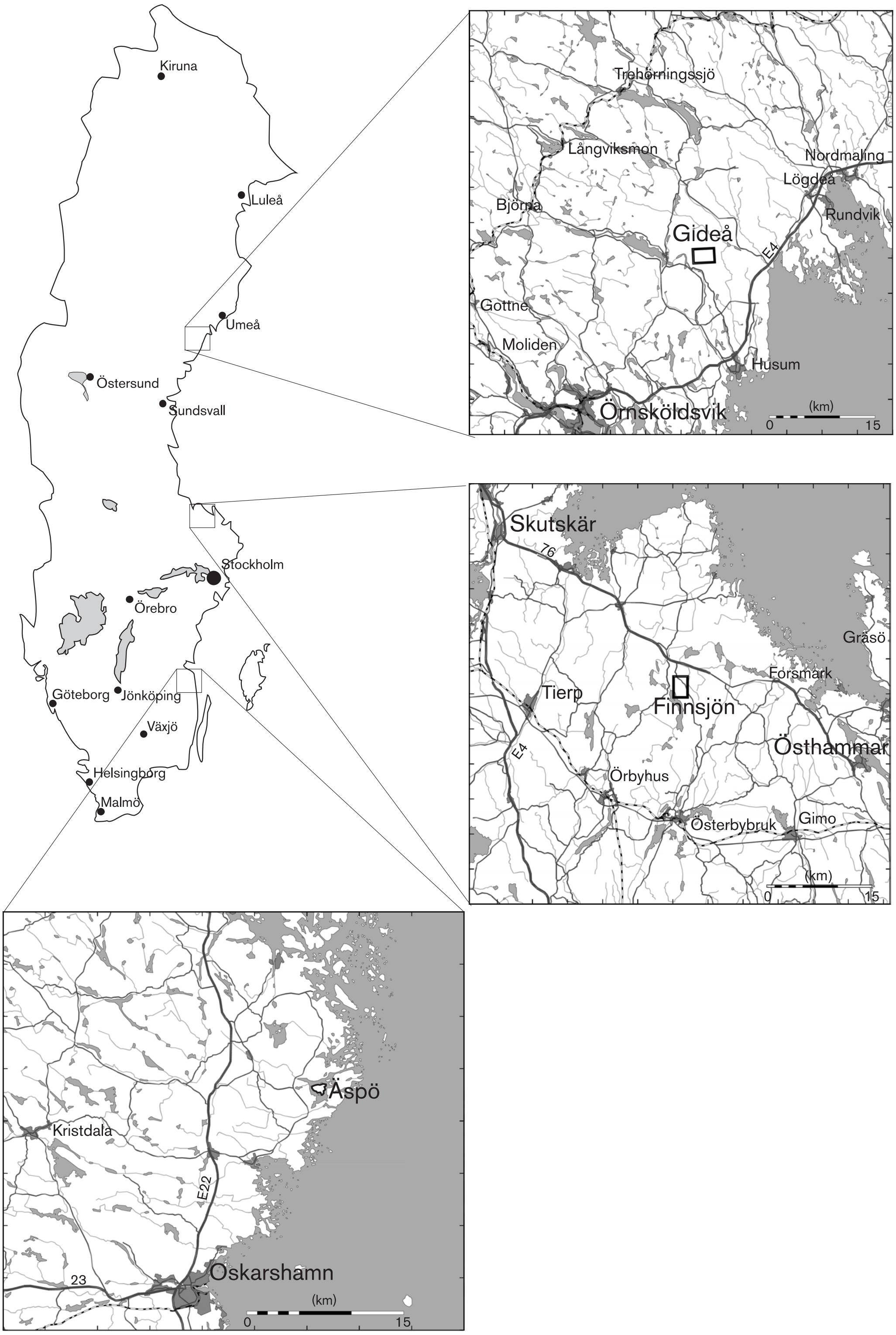

Figure 6-2. *Data for the hypothetical repository sites Aberg, Beberg and Ceberg are taken from Äspö, Finnsjön and Gideå, respectively.*

The groundwater is non-saline. Land uplift is not expected to affect groundwater composition.

6.5.3 Repository geometry/boundary

Initial value

The layout of rock caverns, tunnels and deposition positions in the repository system is based on principles first presented in the KBS-3 study /SKBF/KBS, 1983/, see section 5.2 for a summary description.

A number of possible repository locations have been proposed for Aberg, Beberg and Ceberg and the principal alternative for each site is presented below. The premises underlying the layouts are presented in detail in the Repository System Report and Munier et al /1997/.

A preliminary repository layout was first devised for each repository site to accommodate approximately 4,000 canisters. The total length of the tunnels was chosen so that the canisters spaced at a distance of 6 metres would fit in the repository.

Then the minimum canister spacing required to meet the maximum temperature limit on the canister surface was calculated for each site. These new canister spacings and the same tunnel systems as in the preliminary layout are used in the final repository layout. This means that the number of canisters that are accommodated in the final layout varies slightly between the sites, depending on their different thermal properties. In a fully executed procedure for an actual site, the tunnel system and/or the area of the repository would have to be changed, but this has not been done in SR 97.

In Aberg, the proposed repository layout is split into two levels at depths of 500 and 600 metres so that the entire repository can be fit into the relatively limited study site, see Figure 6-3.

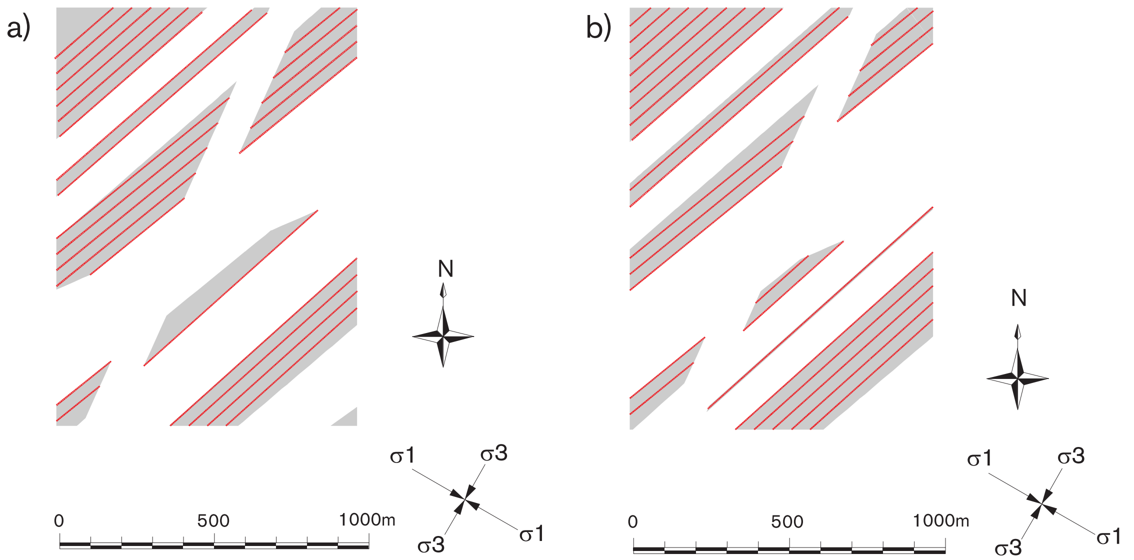

Figure 6-3. *Repository layout for Aberg where the rock blocks have been chosen taking into account the geometry of the hydraulic structures and the respect distance to them. The figure represents cross-sections at a) z = -500 m and b) z = -600 m.*

Thermal calculations carried out for the proposed repository layout in Aberg show that the minimum spacing between the canisters must be increased from 6 m to about 7.5 m if the tunnel spacing is 40 m in order to keep the temperature on the canister surface from exceeding the maximum permissible temperature /Ageskog and Jansson, 1999/.

In Beberg, the proposed layout is located 600 m below sea level so as to avoid a dominant horizontal structure on the site with good margin, see Figure 6-4. Access is via a ramp. The deposition tunnels are oriented perpendicular to the maximum horizontal stress. This direction has been chosen to avoid long intersections with water-bearing fractures with the same direction as the horizontal stress /Munier et al, 1997/. This layout is in close agreement with the one used as an example in the safety assessment SKB 91 /SKB, 1992/.

Thermal calculations carried out for the proposed repository layout in Beberg show that the original spacing between the canisters (6 metres) does not lead to temperatures on the canister surface that exceed the maximum permissible /Ageskog and Jansson, 1999/.

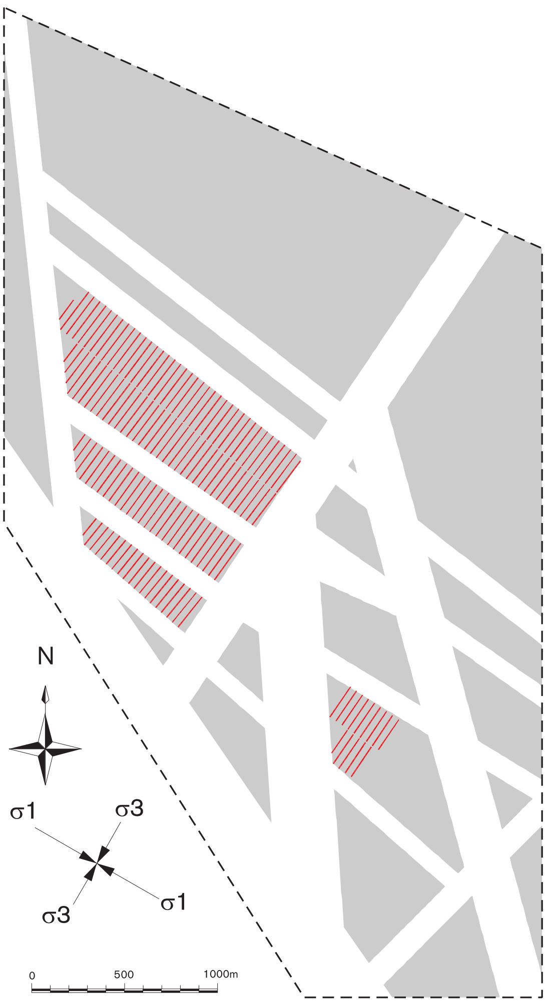

Figure 6-4. *Repository layout for Beberg with deposition tunnels oriented perpendicular to the maximum horizontal stress; z = -600 m.*

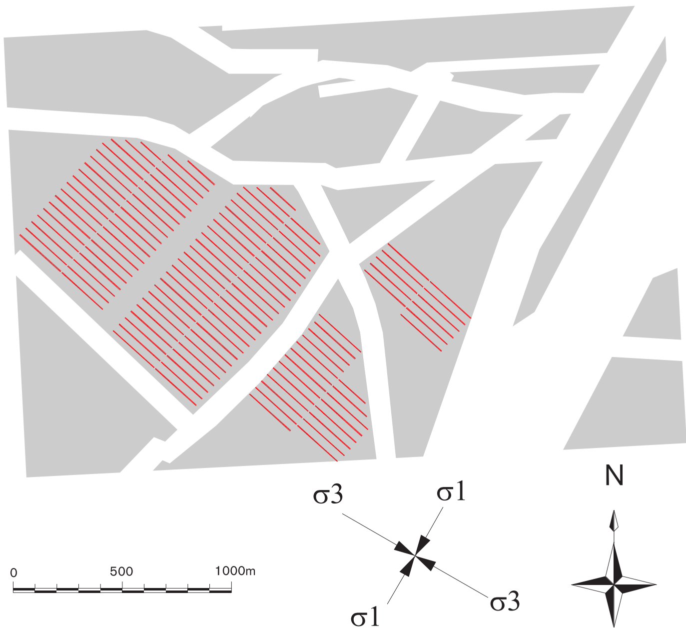

***Figure 6-5.** Repository layout for Ceberg with deposition tunnels oriented perpendicular to the maximum horizontal stress; z = -500 m.*

In Ceberg, the repository is proposed to be located at 500 m below sea level, i.e. around 600 m below the ground surface, see Figure 6-5. Access is via a ramp. The deposition tunnels are oriented perpendicular to the maximum horizontal stress.

Thermal calculations carried out for the proposed repository layout in Ceberg show that the original spacing between the canisters (6 metres) does not lead to temperatures on the canister surface that exceed the maximum permissible /Ageskog and Jansson, 1999/.

Excavation-disturbed zone

Drilling and blasting of tunnels and boring of deposition holes cause fracturing in a zone around hole and tunnel peripheries. Description of this EDZ (excavation-disturbed zone) actually belongs to the variable "fracture geometry", section 6.5.4, but has never-theless been included here since it is a result of repository excavation.

Drilling and blasting of deposition tunnels and other tunnels cause much greater damage to the rock than mechanized mining such as full-face tunnel boring. Blasting damage tests in the Äspö ramp /Pusch and Stanfors, 1992/ and in the ZEDEX tunnel /Emsley et al, 1997/ confirm the preliminary estimates of the extent of the damages that were made in the Stripa project /Börgesson et al, 1992/, as well as the theoretically calculated damages /Andersson, 1994/. The tests in the Äspö ramp and the ZEDEX tunnel indicate a 0.3 m zone outside the walls and roof and a 0.8–1.5 m zone beneath the floor that are significantly affected. The results of hydraulic measurements in the ZEDEX tunnel reveal an increase in permeability in the excavation-damaged zone, but it was not possible to quantify this increase on the basis of the results. Further out from the tunnel, stress redistribution leads to only minor changes, see Figure 6-6.

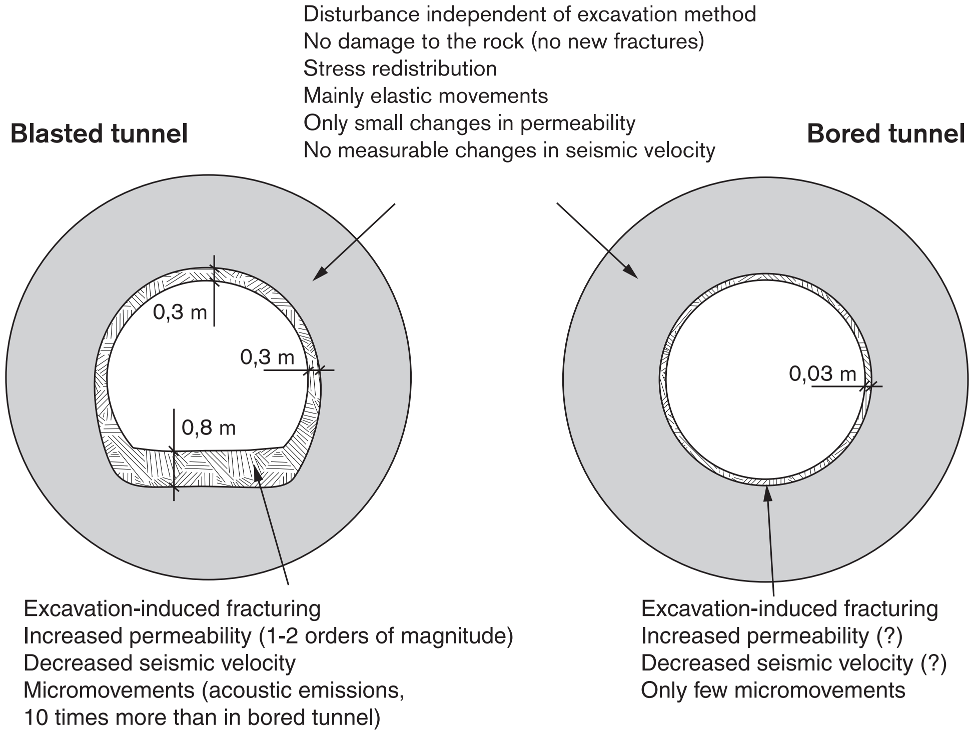

Figure 6-6. *Extent of the disturbed zone (EDZ = excavation-disturbed zone) around a drill-and-blast tunnel as opposed to a TBM tunnel. Compilation of results from ZEDEX experiments in the Äspö HRL.*

Uncertainties

The repository layout will be adapted to the knowledge that exists on the fracture geometry on the different sites. The layouts that are analyzed in SR 97 are described in sufficient detail for the purpose of SR 97. Knowledge of fracture geometry will then be progressively improved in the course of the different phases of the actual siting work, such as site investigation and detailed characterization. The layout of the repository will be fine-adjusted as more and more information is accumulated.

6.5.4 Fracture geometry and permeability

Aberg

The region is dominated by northwesterly, northeasterly and north-southerly steeply-dipping regional fracture zones (termed structures here) with a horizontal extent of more than 10 km (Figure 6-7) /Rhén et al, 1997b/. The fracture zones are often interpreted as having a width of hundreds of metres, with a central fracture portion that can be up to ten or so metres wide. The north-southerly regional fracture zones are presumably the most recently formed and are interpreted to be the most water-bearing according to results of geophysical measurements.

The fracture zones on a local scale have been classified by Stanfors et al /1997/ as major and minor zones, where major zones have a width of more than 5 m. Altogether, 16 fracture zones have been defined within the study site (Figure 6-8). A list of these zones is provided in Table 6-4.The fracture zones are dominated by major zones trending east-westerly and northeasterly, and minor zones trending northwesterly to northeasterly, see Figure 6-8.

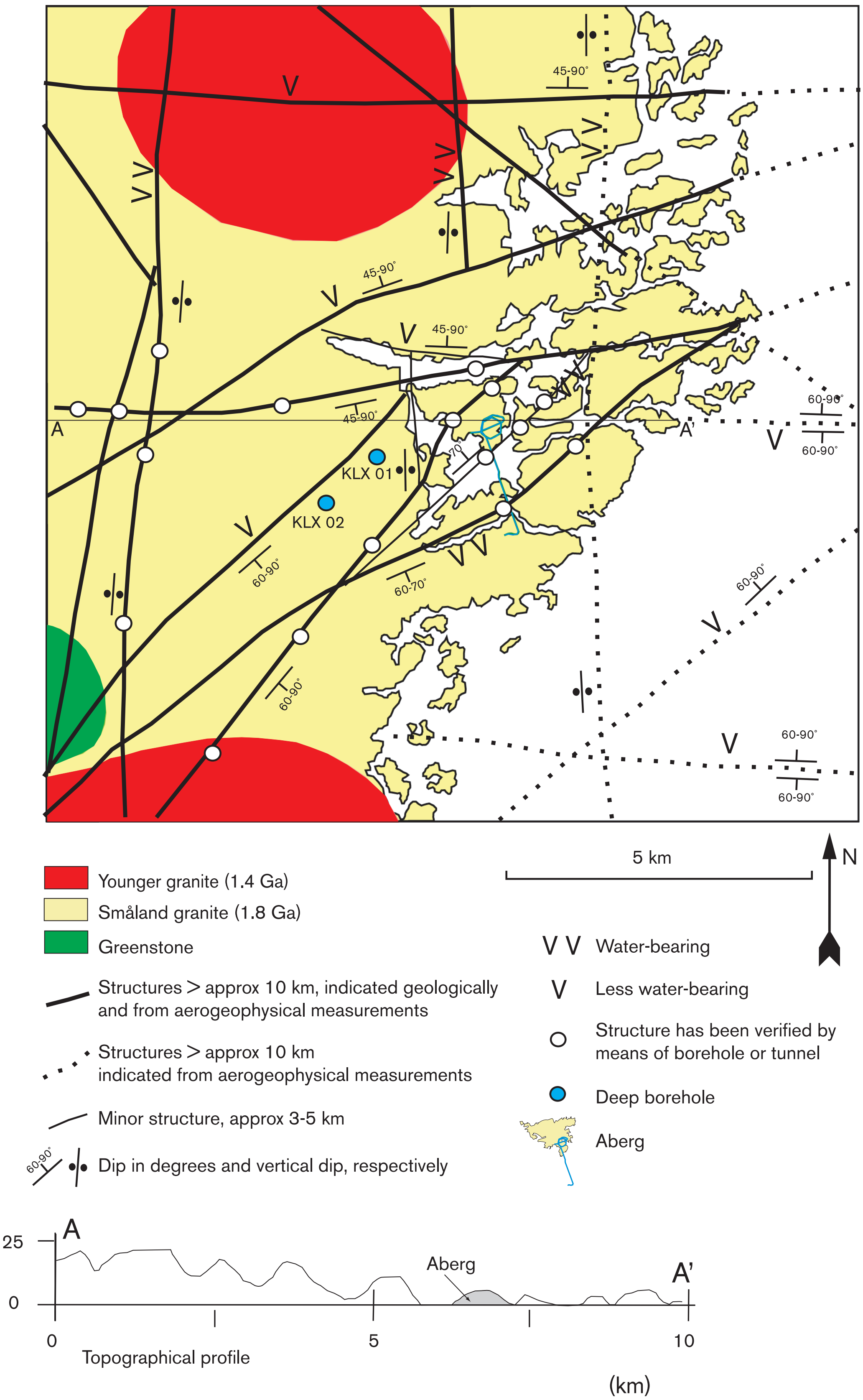

Figure 6-7. Regional geological description of Aberg /after Rhén et al, 1997b/. Topographical profile in east-westerly direction /after Walker et al, 1997/.

Table 6-4. Major fracture zones in Aberg /after Rhén et al, 1997b/. Fracture zone width in parentheses indicates estimated, unobserved average width.

Fracture zone	Dip	Width (m)	Transmissivity mean (m^2/s)
EW-1N	88 SO	(30)	$5.2 \cdot 10^{-7}$
EW-1S	78 SE	(30)	$1.2 \cdot 10^{-5}$
EW-3	79 S	15	$1.7 \cdot 10^{-5}$
EW-7	81 SO	(10–15)	$1.5 \cdot 10^{-5}$
NE-1	70–75 NV	30	$2.2 \cdot 10^{-4}$
NE-2	77 SO	5	$1.2 \cdot 10^{-7}$
NE-3	70–80 NV	50	$3.2 \cdot 10^{-4}$
NE-4	71–78 SO	40	$3.1 \cdot 10^{-5}$
NW-1	30 NO	(10)	$4.1 \cdot 10^{-7}$
NNW-1	(vertical)	(20)	$8.6 \cdot 10^{-6}$
NNW-2	(vertical)	(20)	$2.4 \cdot 10^{-5}$
NNW-3	(vertical)	(20)	$2.0 \cdot 10^{-5}$
NNW-4	85 NO	10	$6.5 \cdot 10^{-5}$
NNW-5	(vertical)	(20)	$4.0 \cdot 10^{-6}$
NNW-6	(vertical)	(20)	$1.4 \cdot 10^{-5}$
NNW-7	85 NO	(20)	$7.5 \cdot 10^{-6}$
NNW-8	(vertical)	(20)	$8.4 \cdot 10^{-6}$

The biggest single zone is a regional northeasterly plastic deformation zone that cuts straight across the island. This zone is designated EW-1 in the geological model. The zone is more than 100 m wide and is clearly indicated by geophysical measurements and in boreholes. It is characterized by heavy foliation and metre-wide mylonites. The Äspö HRL with access tunnel is situated south of the zone.

The fracture zones NE-1, NE-3, EW-3 and NE-4 are all clearly identified by geophysical measurements on the ground surface, in boreholes and tunnels. The zones are characterized by heavily fractured, 10–40 m wide central sections, more or less water-bearing in association with the occurrence of fine-grained granite, greenstone and diorite. NE-2 is a steeply-dipping minor zone that follows a previous mylonite/plastic deformation zone and varies in width between 1 and 5 m.

The minor northwesterly-northeasterly fracture zones are steeply-dipping and have a width that is normally less than 5 m. They are also of smaller extent than the above-mentioned zones. They are locally highly water-bearing and usually consist of one or more fault sets.

Besides superficial stress-relief fractures, only two minor low-dipping fracture zones have been documented from the underground investigations /Rhén et al, 1997a/. They both have a width of about 0.5 m and are visible a hundred or so metres alongside the tunnel.

The number of measured fractures amounts to over 25,000. Of these, about 10,000 have been mapped on outcrops and in trenches. The rest have been mapped in conjunction with the construction of the HRL. The fracture system is divided into four fracture sets with steeply-dipping fractures trending north-south, north-northwest and west-north-west, plus a low-dipping fracture system. Water-bearing fractures tend to be steep and strike west-northwest.

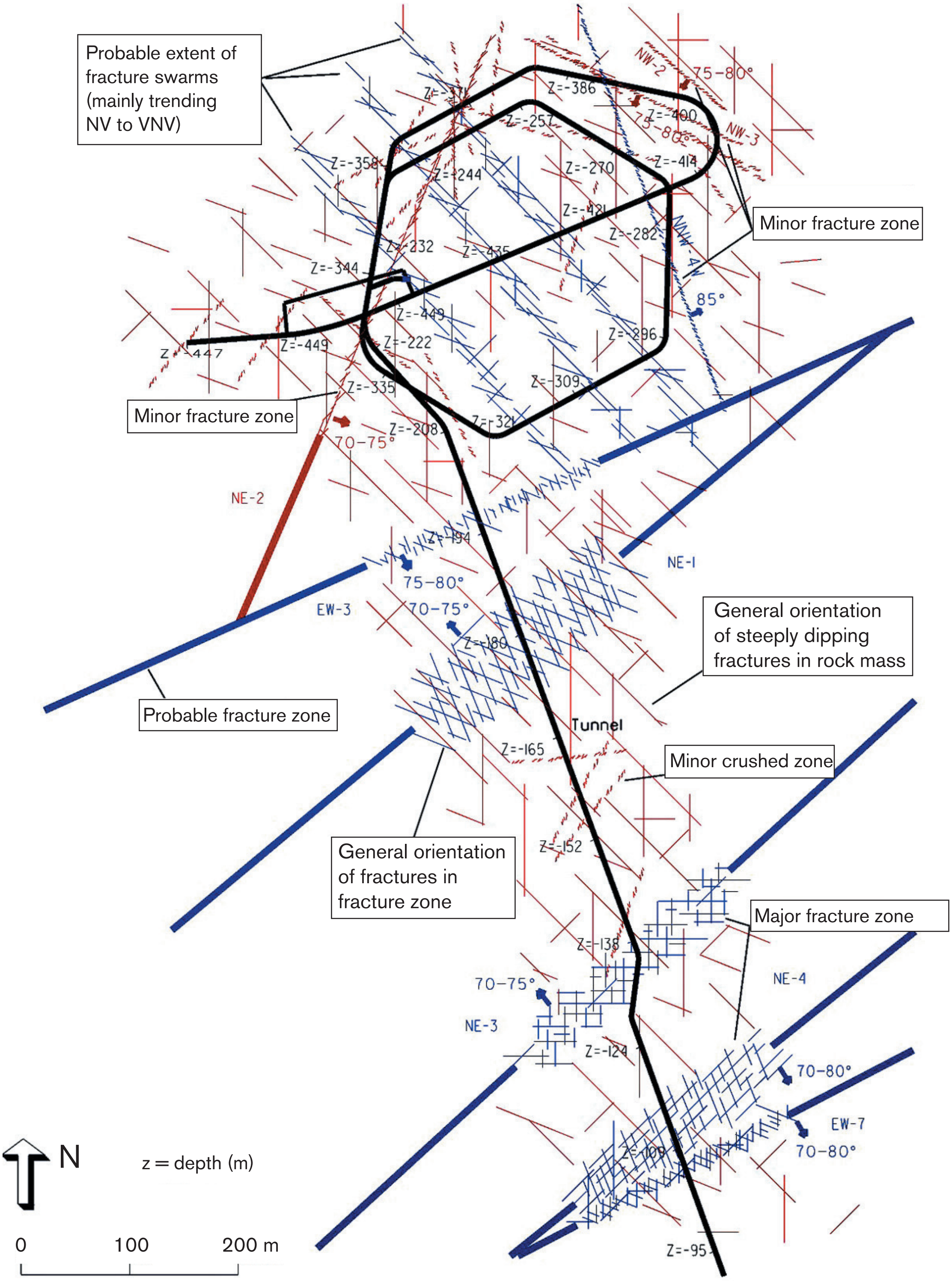

Figure 6-8. Geological-structural model of Aberg study site /after Rhén et al, 1997a/.

Table 6-5. Hydraulic conductivity (m/s) of the rock mass on a local scale for Aberg. The rock mass is divided into five different domains that represent parts of the bedrock with different conductivities. The values are based on 3 m packer tests but are upscaled to a 24 m scale /after Rhén et al, 1997b; Walker et al, 1997/.

Domain	Arithmetic mean log K for 24 m scale
RD1	–8.0
RD2	–7.1
RD3	–8.8
RD4	–7.5
RD5	–7.6
Other RD (mean of RD1–RD3)	–8.5

Hydraulic properties of rock mass and fracture zones have been calculated from 3 m packer tests and hydraulic tests from boreholes drilled from the tunnel.

Hydraulic properties for fracture zones are reported in Table 6-4. The table shows values upscaled to a 24 m scale /after Rhén et al, 1997b; Walker et al, 1997/.

On a local scale, the rock mass has been divided into five domains with different conductivities according to Table 6-5. The rock mass has a dominant fracture direction towards the west-northwest, which means that conductivity may be greater in this direction. Based on investigations in percussion boreholes along the tunnel, Rhén et al /1997b/ have shown that the transmissivity follows the dominant fracture direction. Alternative descriptions of the anisotropy of the rock mass are given by Walker et al /1997/.

Beberg

Regional fracture zones form a block-like network (Figure 6-9). The ground surface in the blocks that are bounded by north-northeasterly fracture zones inclines towards the east-southeast and towards the northeast in the blocks bounded by northwesterly fracture zones. This block inclination is interpreted as being a result of a system of regional faults with a steep dip near the ground surface /Ahlbom and Tirén, 1991/.

A steeply-dipping fracture zone, zone 1, which runs from northeast to southwest, divides the repository area into two halves, the northern and the southern block. Zone 1 is documented to a length of about 5–6 km and has a width of about 20 m. Boreholes through the zone reveal an elevated fracture frequency and an altered, reddish granodiorite.

A subhorizontal fracture zone, zone 2, is situated in the northern block. The zone is approximately 100 m wide and has been identified in nine boreholes in which the upper surface of the zone has been encountered at a depth of between 100–295 m (see the vertical profile in Figure 6-11). There are no indications that zone 2 intersects zone 1 in the southern block, and it has not been identified in outcrops. Zone 2 is believed to have been formed by reactivation of a previous plastic structure. The most intensively fractured sections occur along the upper and lower boundaries of the zone.

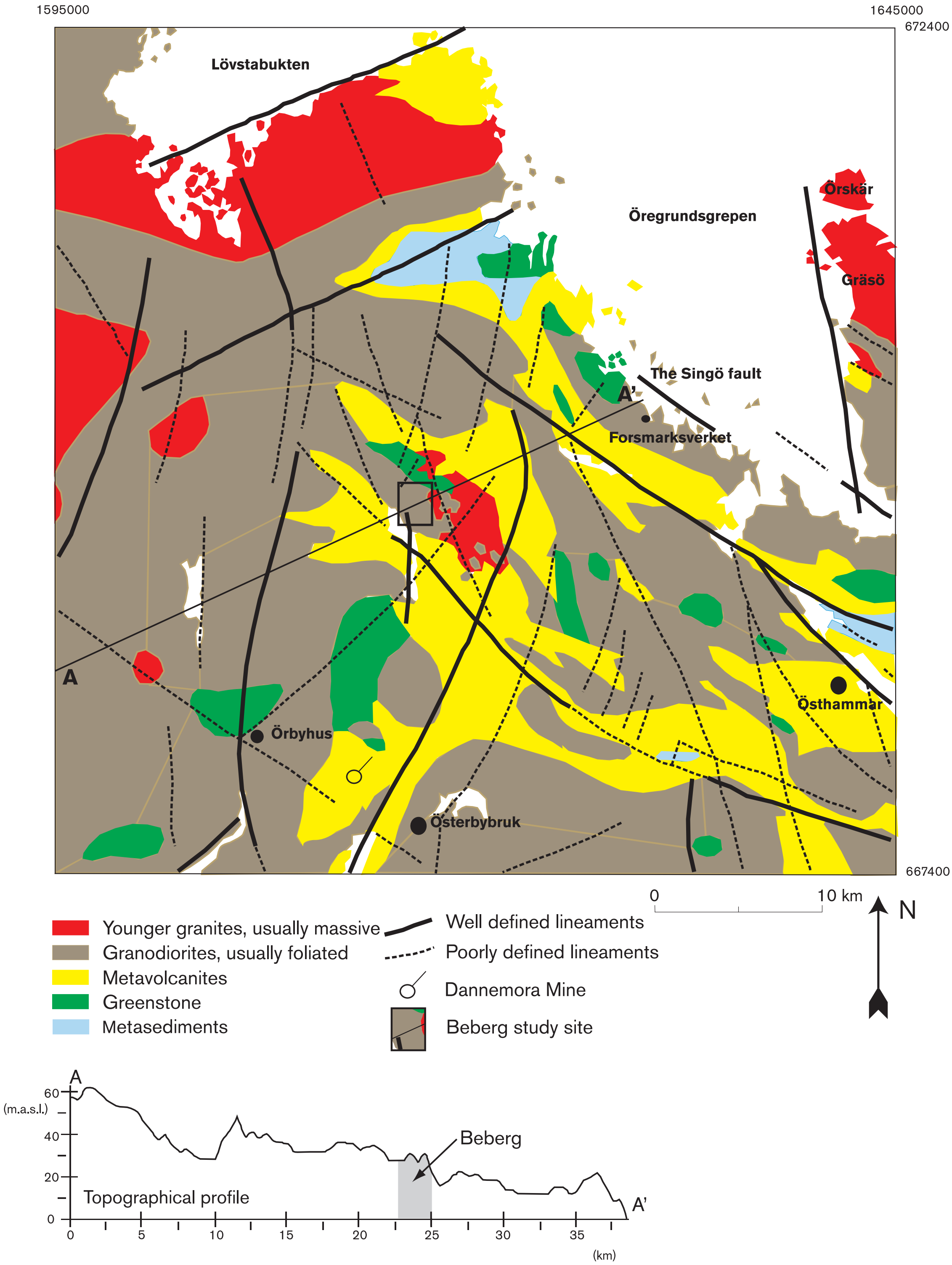

Figure 6-9. Regional geological description of Beberg /after Söderholm et al, 1983; Ahlbom and Tirén, 1991/. Topographical profile in northeasterly direction /after Walker et al, 1997/.

Table 6-6. Fracture zones in Beberg /after Ahlbom et al, 1992; Walker et al, 1997/. Conductivity values are based on 3 m packer tests upscaled to a 100 m scale. K = hydraulic conductivity (m/s).

Fracture zone	Strike	Dip	Width (m)	100 m scale median log K	3 m scale median log K
1	N30O	75SO	20	–4.33	–5.66
2	N28V	16SV	100	–5.15	–6.34
3	N15V	80V	50	–5.63	–6.82
4	N50V	65SV	10	–5.16	–6.35
5	N50V	60SV	5		–6.35
6	N55-65V	60SV	5		–8.39
7	N55V	60SV	5		–7.39
8	N50V	90	5		–7.39
9	N10V	15V	50		–7.94
10	NV	85SV	5		–8.34
11	N5V	35V	100		–7.22
12	N-S	90	25	–4.91	–6.10
13	N30O	75SO	20	–4.33	–5.66
14	NV	90	100	–4.91	–6.10

Besides the zones described above, 12 other fracture zones have been identified. They are summarized in Table 6-6 and Figure 6-10. Several of the zones are less known, particularly within the southern block. Minor shear zones trending northwesterly also occur regularly in the northern block. These zones are usually about 1–5 m wide and extend a hundred metres or so.

The fracture system is dominated by steeply-dipping northeasterly and northwesterly fractures and by low-dipping fractures. The mean fracture frequency in the southern block is about 3 fractures per metre, measured along two perpendicular profiles along the ground surface and in the uppermost 100 m in the cored boreholes /Olkiewicz and Arnefors, 1981; Ahlbom et al, 1992/. No decrease in the fracture frequency has been noted with depth. In the northern block, on the other hand, the measured frequency is only 1.5 fractures per metre based on measurements in outcrops. Boreholes in this block exhibit a similar fracture frequency.

The hydrogeological model, which is based on a geological-structural model by Andersson et al /1991/, differs between the rock mass (rock domain) and fracture zones (conductor domain). The rock mass is in turn divided into a southern and a northern block. Table 6-7 shows hydraulic conductivity at different depths in the rock mass. The conductivity is calculated from 3 m packer tests and upscaled to 24 m blocks /after Rhén et al, 1997b; Walker et al, 1997/.

In addition to this base case, Walker et al /1997/ propose alternative explanation models in which the rock mass is regarded as anisotropic and dependent on the dominant fracture direction and the stress field in the area.

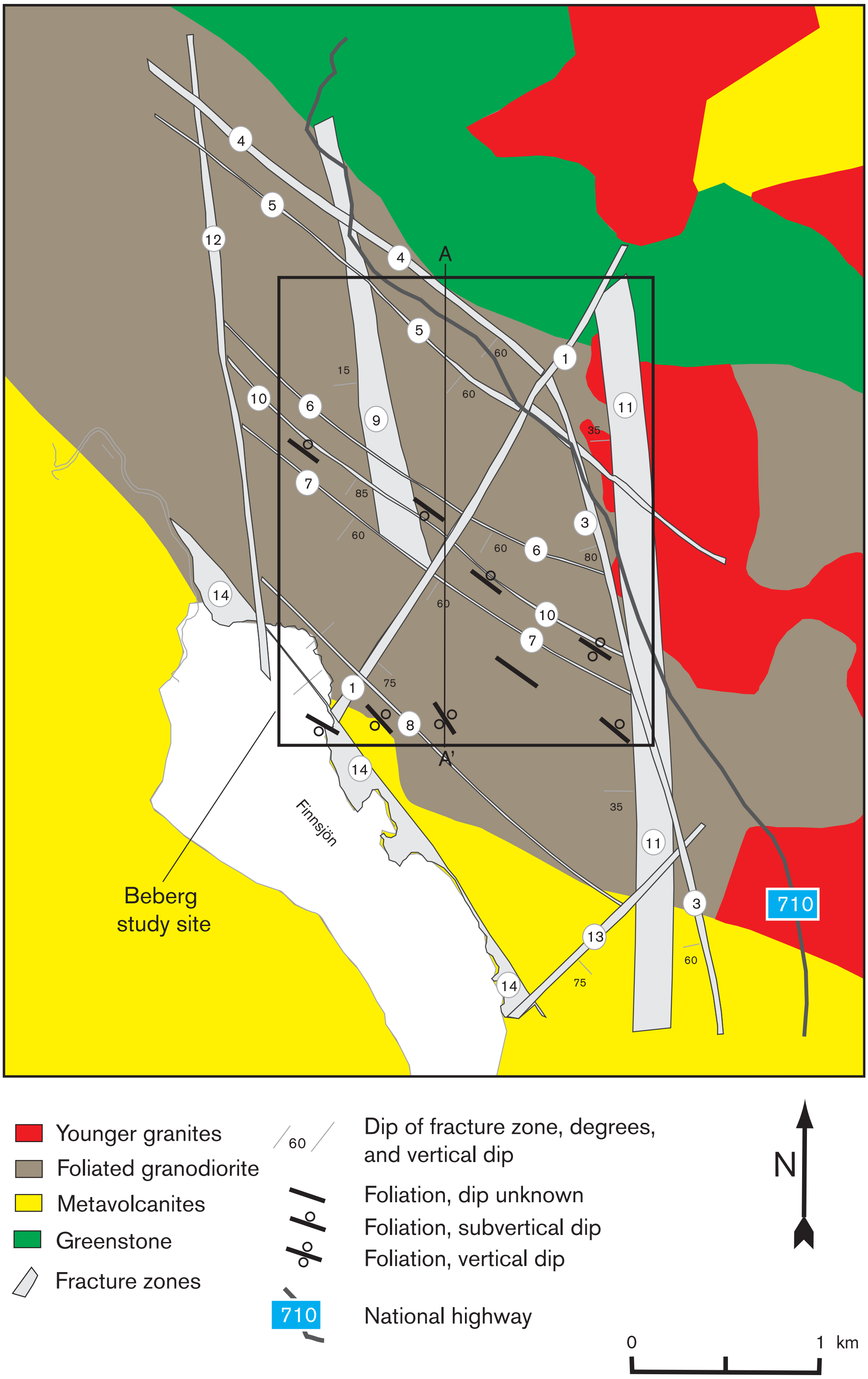

Figure 6-10. Bedrock map and generalized picture of fracture zones in Beberg /after Ahlbom and Tirén, 1991; Ahlbom et al, 1992/.

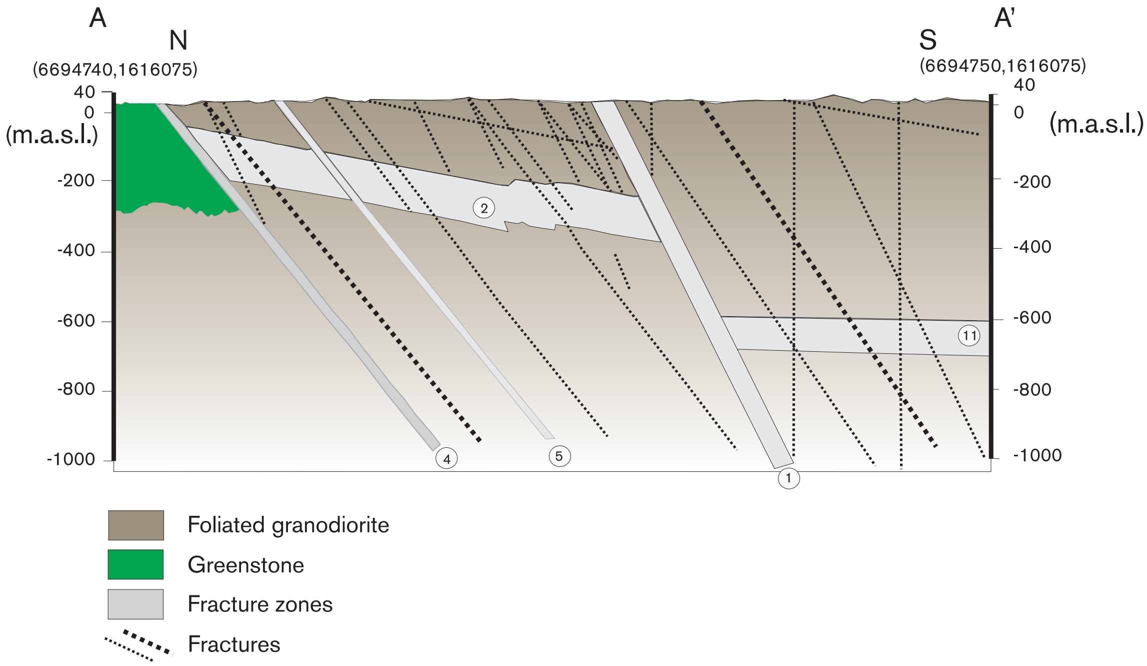

Figure 6-11. *North-southerly vertical profile through the Beberg study site /after Ahlbom and Tirén, 1991/. For the path of the profile, see the profile A–A' in Figure 6-10.*

Table 6-7. Hydraulic conductivity (m/s) of the rock mass on a local scale for Beberg. The values are based on 3 m packer tests but are upscaled to 24 m /after Rhén et al, 1997b; Walker et al, 1997/.

Elevation (m.a.s.l.)	Arithmetic mean log K for 24 m scale
Northern block	
above −100	−6.6
−100 to −200	−7.2
−200 to −400	−7.8
below −400	−7.6
Southern block	
above −100	−6.8
−100 till −200	−7.8
−200 till −400	−8.1
below −400	−7.9
Remaining rock mass	
above −100	−7.8
below −100	−7.8

Ceberg

The regional fracture zones (lineaments) are interpreted as being steeply-dipping with a predominantly west-northwesterly to northwesterly direction /Ahlbom et al, 1983; Askling, 1997; Walker et al, 1997/, Figure 6-12. According to Askling /1997/, there may be a regional fracture zone in the northeast corner of the site. However, no boreholes intersect the fracture zone, and geophysical surveys in the area have failed to indicate the zone. A small number of other lineaments cross the area and can be correlated to existing fracture zones. Despite the fact that several boreholes intersect these zones, their geological and hydraulic properties should be regarded as uncertain /Ahlbom et al, 1983; Askling, 1997; Hermansson et al, 1997/.

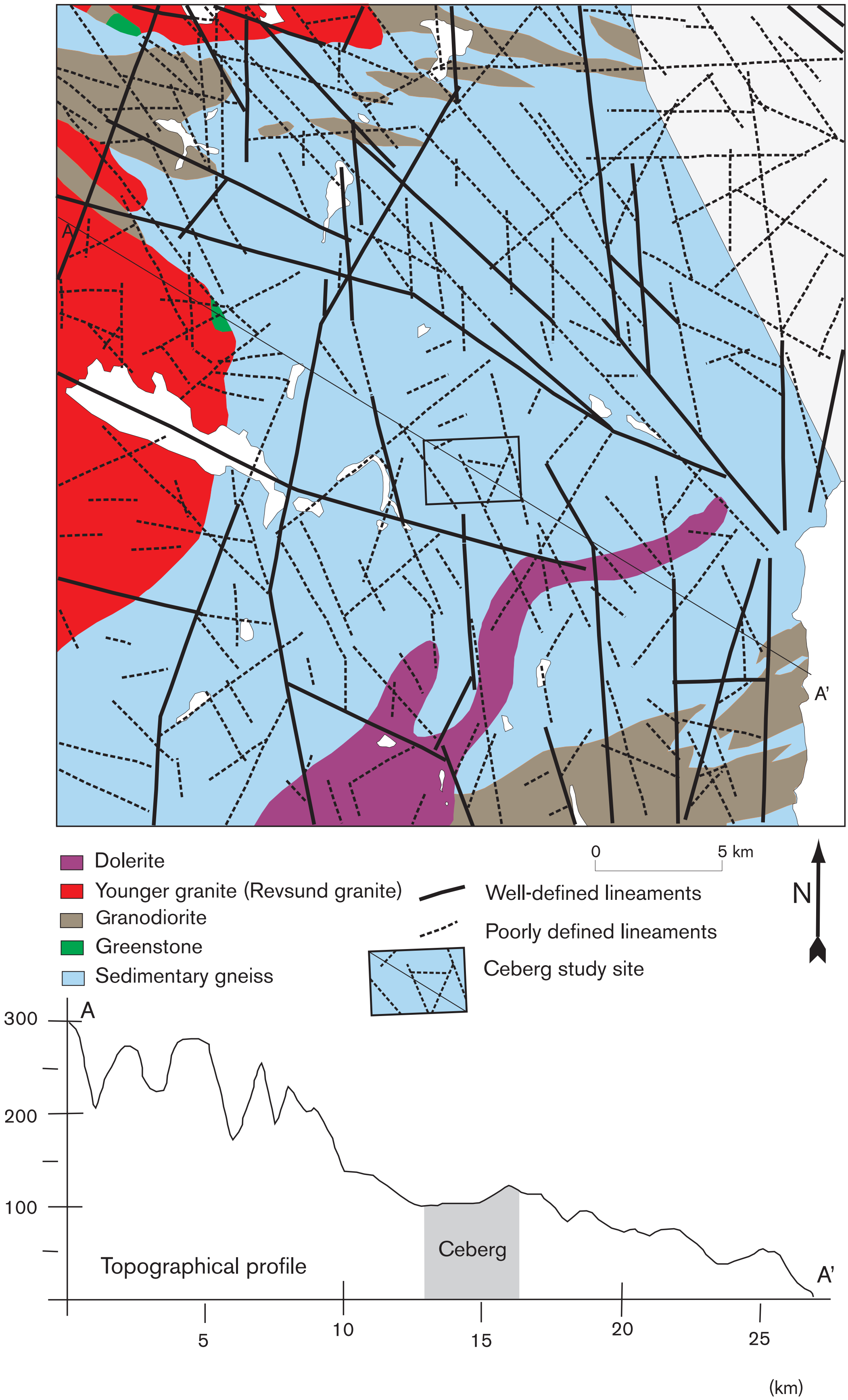

Figure 6-12. Regional geological description of Ceberg /after Ahlbom et al, 1983; Walker et al, 1997/. Topographical profile in northwesterly direction /after Walker et al, 1997/.

Table 6-8. Fracture zones in Ceberg /after Hermanson et al, 1997/. Conductivity values are based on 25 m packer tests, upscaled to a 100 m scale /after Walker et al, 1997/.

Fracture zone	Strike	Dip	Width (m)	Hydraulic conductivity (m/s)
1	NNO	Brant O	41	$< 5 \cdot 10^{-12}$
2A	NNO	80 O	7–16	$1 \cdot 10^{-8} - 2 \cdot 10^{-6}$
2B	NNO	60 O	35	$1 \cdot 10^{-7} - 5 \cdot 10^{-6}$
3A	O-V	30 N	11–30	$1 \cdot 10^{-7} - 1 \cdot 10^{-10}$
3B	O-V	Brant N	4–12	$7 \cdot 10^{-11} - 7 \cdot 10^{-12}$
4	O-V	Brant N	9	$7 \cdot 10^{-12}$
5	O-V	Brant N	50	
6	NNO	70 SO	3–10	$5 \cdot 10^{-9} - 5 \cdot 10^{-12}$
7	NNV	75 O	8	$7 \cdot 10^{-10} - 7 \cdot 10^{-11}$
8	NV	Brant SO	10	
9	O-V	N	5	
10	N-S	90	5	
11A	ONO	75 SO	25	$5 \cdot 10^{-7}$
11B	ONO	75 SO	13	$2 \cdot 10^{-6}$
12	ONO	75 SO	10	$5 \cdot 10^{-6} - 2 \cdot 10^{-10}$

15 fracture zones with a width of 5–50 m have been identified on the study site, see Table 6-8 and Figure 6-13. Most zones have been located by means of geophysical measurements and verified in percussion boreholes and later also in cored boreholes.

The fracture zones intersect all rock types in the area and do not follow any rock type boundaries, but may have been influenced by foliation. No low-dipping zones have been observed down to a depth of 700 metres. Saksa and Nummela /1998/ point out, however, that low-dipping fracture zones may occur in conjunction with possible flat dolerite dykes at depths below 700 m. Vertical profiles in Figure 6-14 show both dolerite dykes and fracture zones.

The fracture zones are generally identified by means of an elevated fracture frequency, sections of crushed core and water losses. Both fracture zones and dolerite dykes usually contain clay-altered sections.

For the local hydromodelling, Ceberg is divided into two conductivity domains: the rock mass domain and a conductor domain consisting of fracture zones. The division is based on the structural model by Hermanson et al /1997/. The domains differ through relatively low conductivities in the rock mass compared with the conductor domain /Walker et al, 1997/. The hydraulic conductivity of the rock mass, given in Table 6-9, is based on 25 m packer tests.

Hydraulic properties for fracture zones were tabulated in Table 6-8.

Table 6-9. Hydraulic conductivity K (m/s) of the rock mass on a local scale for Ceberg. The values are upscaled to a 25 m scale /after Walker et al, 1997/.

Elevation (m.a.s.l.)	Arithmetic mean log K for 25 m scale
+110 to 0	−7.6
0 to −100	−9.0
−100 to −300	−10.0
below −300	−10.3

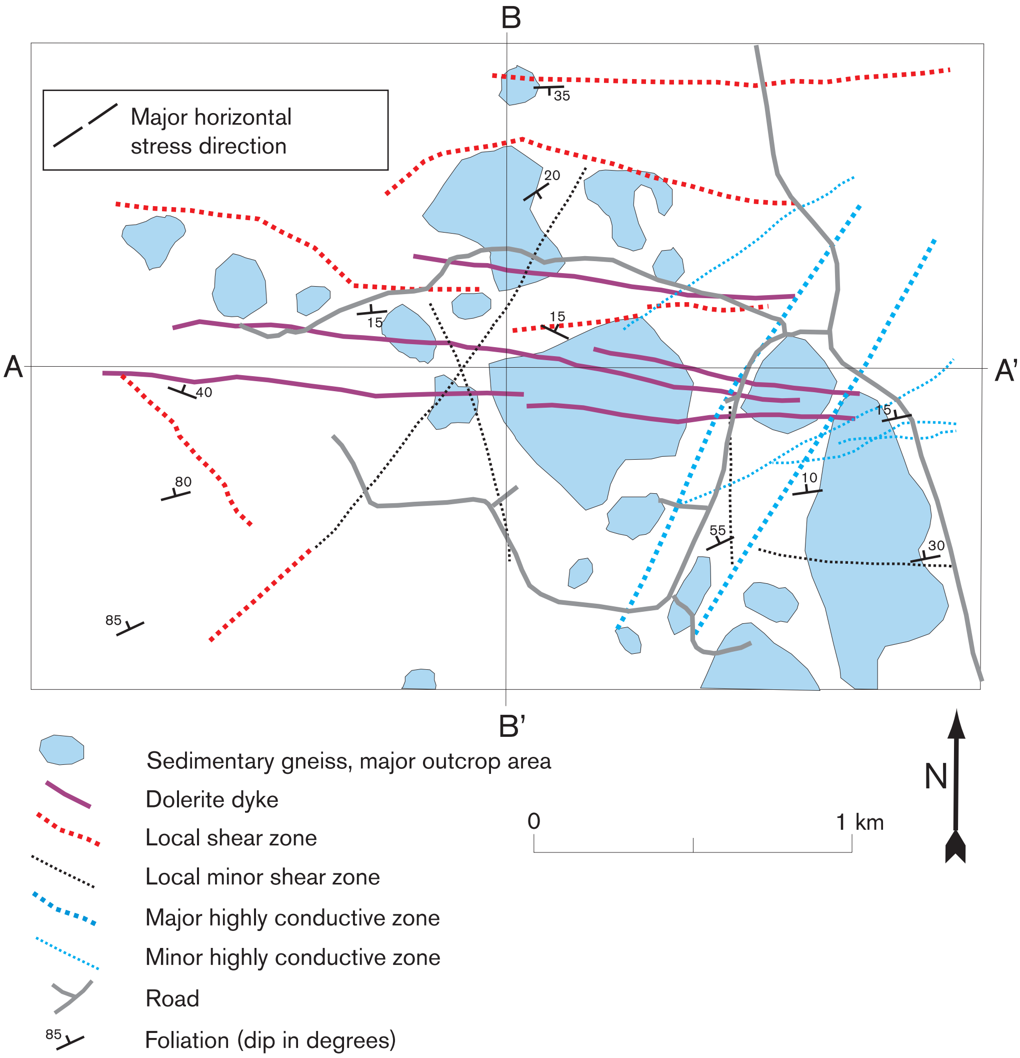

Figure 6-13. Geological-structural model of Ceberg /after Ahlbom et al, 1991; modified by Hermansson et al, 1997/.

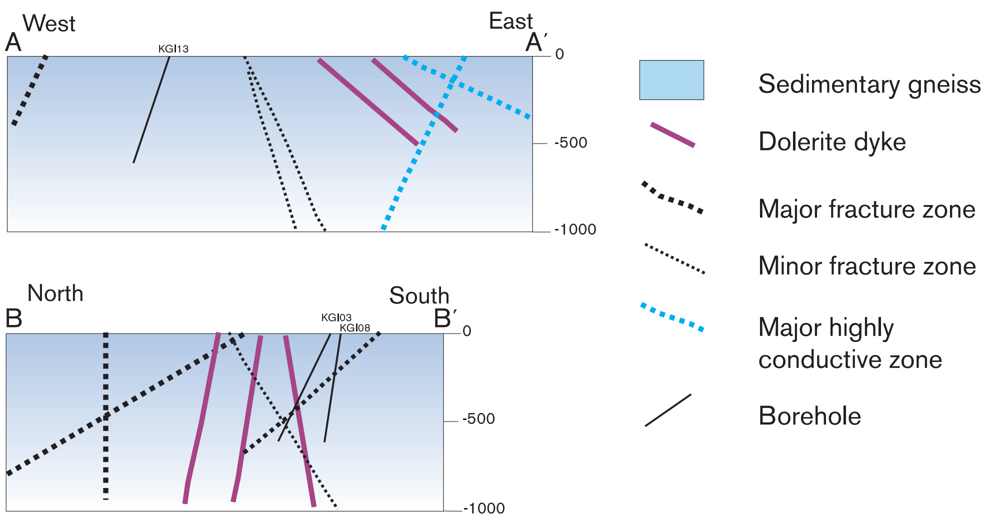

Figure 6-14. Vertical profiles in north-southerly and east-westerly direction /after Ahlbom et al, 1991/.

Uncertainties

In the case of the structures in the regional structural model (regional fracture zones), uncertainty with respect to the lateral geographic position of the structures is estimated to be between 100 and 200 m, when only aerogeophysical and lineament indications are available. In cases where the position of the structures has been verified by ground geophysics, geological field observations and drilling, the uncertainty decreases considerably (5–20 m).

Uncertainty in the dip and character of the zones is very great (20–30 degrees) if only geophysical data are available. Geological field observations, and above all drilling, increase certainty considerably but are often based on single sections through the zone. Relatively great uncertainty regarding dip and character therefore almost always exists for a major structure, unless very extensive investigations have been conducted.

The three sites are located in different geological settings, all of which are representative of Swedish bedrock outside the Caledonide mountains. The Data Report summarizes the uncertainties that influence the geological description. The predominant uncertainty stems from the limited availability of data used to describe a large volume. There may be many reasons for a limited data quantity, such as inaccessible terrain with few outcrops, time limitations that do not permit a complete geological mapping, or surveys that only cover a part of the site.

Site-specific uncertainties for the geological-structural models used for Aberg, Beberg and Ceberg are discussed by Saksa and Nummela /1998/:

- The geological models of rock mass and fracture zones that are used are largely devised using the same methodology. The greatest uncertainty is the description of fracture zones on the scale from 10 to 300–1,000 metres length.
- Aberg lacks a delimited study site. If the island of Äspö is used to delimit the site, there are indications that the rock volume within the site comprises a highly tectonized portion of the region. This means that borehole data from southern Äspö are not necessarily typical for the entire area.
- There are relatively great uncertainties in the geological description and thereby in the fracture geometry for Beberg and Ceberg.

As regards the hydraulic conductivity of the fracture zones and the rock mass, the properties vary in space, as is illustrated by the standard deviation of the hydraulic conductivity. The difference in hydraulic conductivity between different blocks on the 30 m scale can amount to a factor of one hundred or more. The spatial variation does not constitute an uncertainty in itself, being rather a property of the rock, but the situation for high-conductive versus low-conductive areas can only be determined statistically on the basis of the information that can be obtained from boreholes (site investigation). The spatial variation and the statistical uncertainty are handled with the stochastic continuum description that is used to analyze groundwater flow (see Chapter 9). Investigations directly from deposition tunnels (detailed characterization) do not diminish the spatial variation, but will yield much greater knowledge of where high- and low-conductive areas are situated. In a safety assessment performed on such detailed information, it is thereby possible to take account of the fact that deposition holes have been placed in the low-conductive areas. Such a local optimization of the repository, which could lead to considerably improved performance, has not been done in SR 97.

Furthermore, there are relatively great uncertainties pertaining to the actual conductivity values for rock mass and fracture zones:

- There are alternative options for dividing the rock into fracture zones and rock mass (see above).
- The interpretation of different hydraulic tests used to obtain conductivity values is limited by simplifications and assumptions.
- There are different explanation models as to how the high-conductive areas in the rock are interrelated, which leads to uncertainties as to how test results from a small scale are to be upscaled to calculations performed on a larger scale.
- Hydraulic conductivity could be direction-dependent.

The Data Report discusses these uncertainties relatively thoroughly.

In SR 97, the above uncertainties are handled mainly by formulating and analyzing a number of alternative interpretations of the hydraulic information. Furthermore, different conceptual models are studied. The resultant uncertainty in groundwater flow is then considered when data are determined for radionuclide transport calculation (see the analysis of the canister defect scenario in Chapter 9).

6.5.5 Temperature

Initial value

The heat flow at a depth of 500 m in Swedish bedrock has been compiled in the Repository System Report /after Sundberg, 1995/ and is based on information from some sixty boreholes, mostly deep and drilled in conjunction with mine prospecting, geothermal prospecting or in SKB's siting studies. The geothermal gradient at Aberg, Beberg and Ceberg is reported in the same report.

Uncertainties

See discussion in Ahlbom et al /1995/.

6.5.6 Groundwater flow

Initial value

The groundwater flow is determined by the rock's water-conducting capacity in combination with the hydraulic gradient. A description of the flow situation on the sites is provided in the hydraulic evolution in the base scenario, section 8.7.2.

6.5.7 Groundwater pressure

The gradient for the groundwater head is the most important driving force for groundwater flow; the lower the gradient, the lower the groundwater flow. On a large scale, the gradient does not vary as much as the rock's conductivity, but is determined to a high degree by the topographical variation.

The natural gradient on the three sites in SR 97 is: Aberg 0.05–0.2 percent, Beberg 0.2–0.3 percent, Ceberg 0.5–0.6 percent at typical repository depth /after Walker et al, 1997/.

6.5.8 Gas flow

Gas flows in the repository are handled qualitatively. The concentrations of dissolved gas that occur naturally in the groundwater cannot form a separate gas phase. Gas that entered during construction may be present in the repository initially. Such gas is expected to dissolve in the groundwater and it is therefore not meaningful to talk about gas flows initially.

6.5.9 Rock stresses

The site-specific body of rock-mechanical data consists primarily of results from rock stress measurements and laboratory determinations of deformation and strength properties of drill core specimens. Rock Mass Rating (RMR) Results are also available to a varying extent.

Aberg

The body of rock-mechanical data from Aberg differs from that from other sites in two respects. One is the much greater scope of investigations and data. The other, and more important, difference is that both data from borehole investigations and practical experience from construction and operation of a rock facility are available from the area.

Before the Äspö HRL was built, rock stress measurements were made to a depth of at most about 900 metres in three near-vertical boreholes /Bjarnason et al, 1989/. The methods used were hydraulic fracturing and overcoring. The measurements were supplemented by rock-mechanical laboratory tests of drill cores. Further measurements were then carried out during excavation and operation of the facility, exclusively by overcoring, in a number of short (up to about 20 m) boreholes at different levels, down to a maximum depth of about 450 metres.

Altogether, a large quantity of rock stress data are thus available from Aberg. Figure 6-15 summarizes the available data. The figure shows that the state of stress in the horizontal plane is decidedly anisotropic throughout, i.e. the maximum horizontal stress is much greater than the minimum ($\sigma_H >> \sigma_h$). The values of σ_H, as well as the rate of increase with depth, are slightly higher than average for Swedish crystalline bedrock, but cannot be said to be abnormally high. The direction of the maximum horizontal stress is north-west-southeasterly with some variation, regardless of depth. This agrees well with both measurements in the nearby Laxemar area /Ljunggren and Klasson, 1997/ and trends on a national scale /Stephansson et al, 1991; Ljunggren and Persson, 1995/. The vertical stress is much lower than the maximum horizontal stress and agrees, at least on average, fairly well with the lithostatic load.

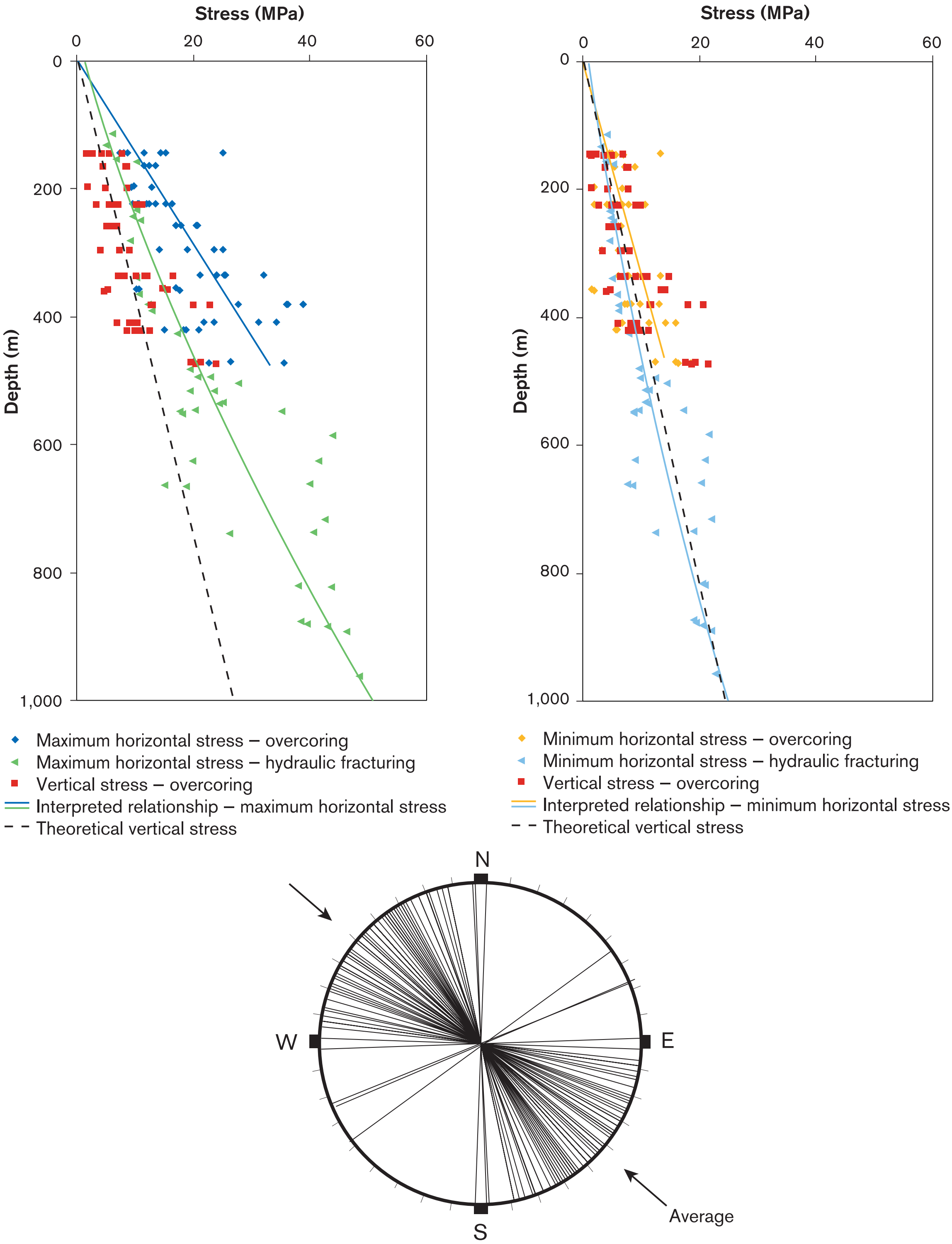

Figure 6-15. *The rock stress situation in Aberg. The sum as a function of depth for measured horizontal and vertical stress components. The direction of the maximum horizontal stress, on average and for individual measurement points, are also shown.*

Beberg

The rock-mechanical measurements that have been performed at Beberg are rock stress measurements plus a few laboratory tests of core specimens.

Bjarnason and Stephansson /1988/ report the results of rock stress measurements in a vertical borehole. The measurements were performed by hydraulic fracturing, which means that the results are limited to stress components in the horizontal plane. The results are presented in Figure 6-16, and consistently reveal a stress situation that is very typical for Swedish crystalline basement rock. This means horizontal stresses that are slightly higher than the theoretical vertical stress (the lithostatic load) and that increase gradually with depth to sums of 15–25 MPa at a depth of 500 metres. The maximum horizontal stress is oriented in a northwest-southeasterly direction.

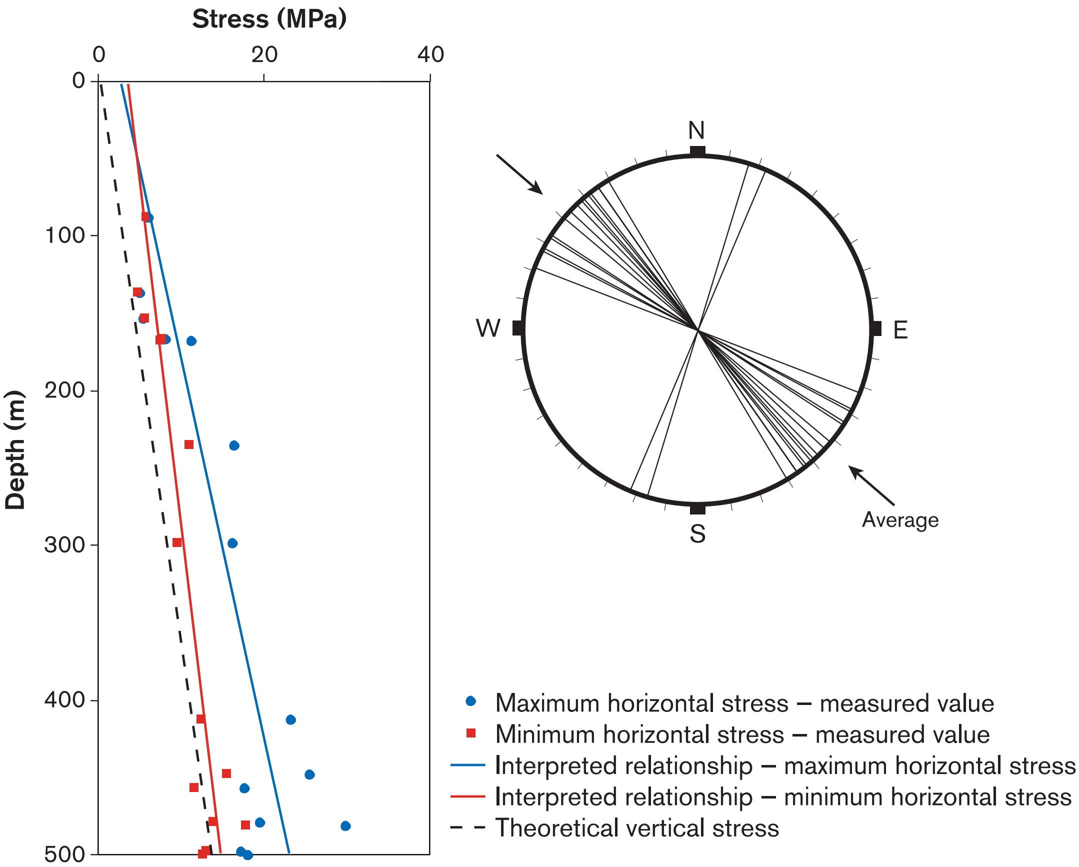

Figure 6-16. *The rock stress situation in Beberg. At left the sum as a function of depth for measured horizontal stress components (theoretical vertical stress is shown as comparison). At right the direction of the maximum horizontal stress, on average and for individual measurement points. All data from measurement by hydraulic fracturing in a vertical borehole.*

Ceberg

Rock-mechanical data from Ceberg are of roughly the same nature and scope as from Beberg. Rock stress measurements were performed in a borehole and laboratory determinations of mechanical properties were performed on core specimens from the same borehole. Data were compiled and reported by Ahlbom et al /1991/.

The rock stress measurements were performed by hydraulic fracturing, from the surface and down to a depth of about 500 metres, in a near-vertical borehole. The results are shown in Figure 6-17. The measured stress sums are all normal for Swedish crystalline bedrock. The minimum horizontal stress is comparable in terms of sum and gradient to the theoretical vertical stress. Data also indicate that the rate of increase of the rock stresses with depth diminishes below a depth of 300 metres, which is the reason for the interpreted relationships in Figure 6-17. This interpretation is uncertain, however, and finds no apparent support in the geological information from Ceberg.

According to Figure 6-17, the direction of the maximum principal stress is northeast-southwesterly, but with great variations and without tendencies towards rotation with depth. This deviates from the general trend of a predominantly northwest-southeasterly stress direction. Such local deviations have been noted in many places and are thus not unusual. The possibility that the direction determinations contain significant measurement errors cannot be ruled out. This suspicion is based on the fact that the rock type

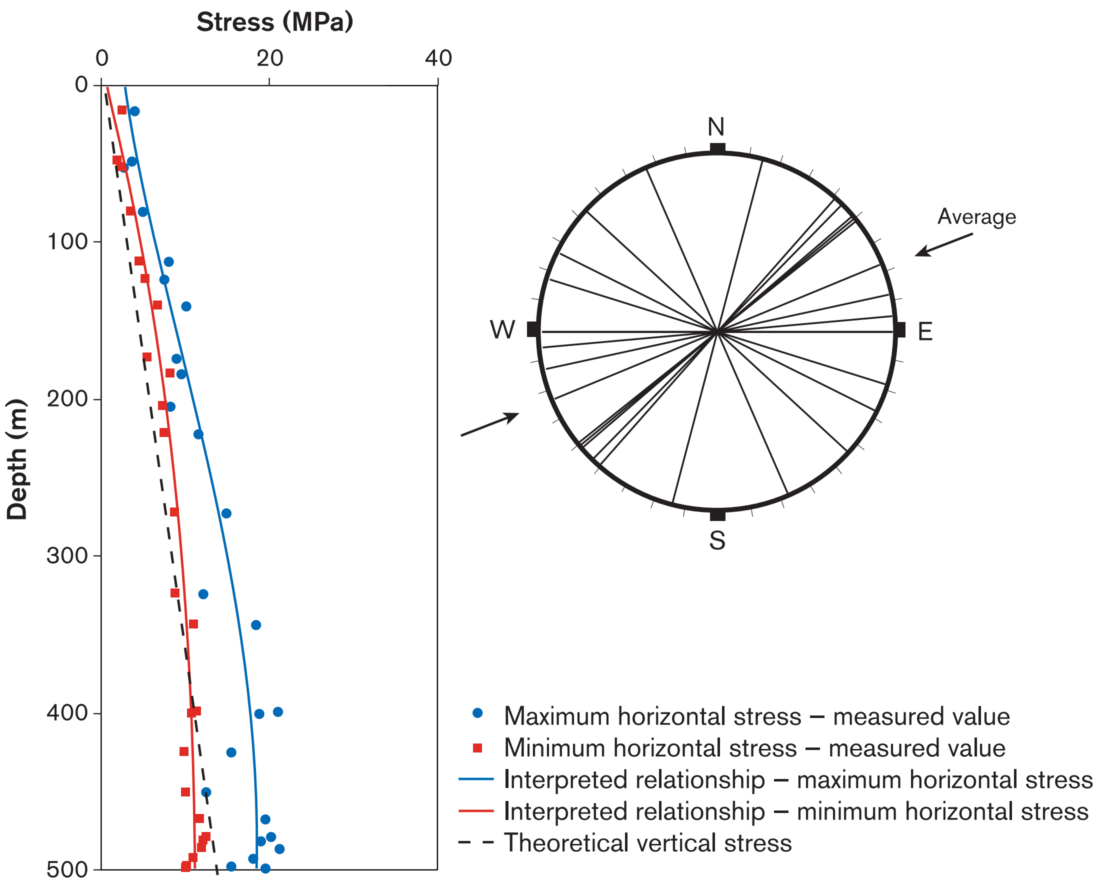

Figure 6-17. *The rock stress situation in Ceberg. At left the sum as a function of depth for measured horizontal stress components (theoretical vertical stress is shown as comparison). At right the direction of the maximum horizontal stress, on average and for individual measurement points. All data from measurement by hydraulic fracturing in a vertical borehole.*

exhibits a steeply-dipping foliation, which may have influenced fracture generation in connection with hydraulic fracturing, and thereby the measurement values for stress directions.

Uncertainties

Rock stress measurements yield point values. The measurement methods for rock stresses are less exact than is the case for mechanical properties, at the same time as the spatial variation is greater and more difficult to link to the local geology. In measurements in good rock and load levels that are typical for depths around 500 m, the uncertainty of individual measurements is usually estimated at a few tens of percent. The uncertainties in the rock stress data are of greatest importance for assessment of how the deep repository should be built. Their influence on long-term safety is less important.

In general, the crucial uncertainties seldom lie in the mechanical properties of the rock or in the rock stresses, as individual components. They lie instead in the understanding of how the mechanical system of rock mass and cavities will behave under the loads and scale in question. The uncertainties usually apply above all to the bearing capacity of the rock mass (including fractures and fracture zones), deformation patterns and possible fracture mechanisms. Experience feedback from practical cases is the principal method for reducing these uncertainties. The uncertainties therefore increase markedly in cases where previous engineering applications against which forecasts and judgements can be verified are lacking. Such is the case with the rock-mechanical assessments that are made in conjunction with performance and safety assessments of the deep repository, mainly because they involve timespans that vastly exceed those in the experience base. The long-term rock-mechanical changes are therefore discussed thoroughly in the base scenario (Chapter 8) and in the various scenarios that involve changes in the mechanical environment (climate and tectonics scenarios).

6.5.10 Matrix minerals

All sites are examples of Swedish crystalline bedrock, but of differing character. A detailed rock type description is given in the Repository System Report.

At Aberg the rock is dominated by four types of rocks: Ävrö granite (Småland granite), Äspö diorite, greenstone and fine-grained granite. Both Äspö diorite and Ävrö granite can be regarded as variants of Småland granite /Kornfält and Wikman, 1988; Wikman and Kornfält, 1995/. The Äspö diorite has been dated at about 1,800 million years and dominates the rock type distribution compared with the somewhat younger Ävrö granite. The Äspö diorite has a slightly more basic character than the Ävrö granite and is normally grey to greyish-red.

The bedrock at Beberg is dominated by a grey granodiorite with a depth of at least 700 m (the deepest borehole). The granodiorite has a steeply-dipping northwesterly foliation. Dykes of basic rock types, pegmatites and aplites, intersect the granodiorite. Older altered acid volcanites occur west and south of the area. Basic rock types occur as elongated xenoliths running along the foliation.

Ceberg is dominated by sedimentary gneiss (metagreywacke) and blocks of older granite. This bedrock is intersected by vertical east-westerly dolerite dykes that can be up to 15 m wide. Thicker sills of dolerite probably overlay the site earlier. Even though no sills have been encountered down to a depth of 700 m, Saksa and Nummela /1998/ do not exclude the possibility that they could be found at greater depth.

Uncertainties

The exact location and boundaries of the different rock types are only partially known. Which rock type dominates is of less importance for the retarding function of the geosphere. Sorbency varies much more with e.g. pH and Eh changes than with rock types. The degree of weathering and alteration of the rock is of some, but not crucial, importance for sorption /Carbol and Engkvist, 1997/.

6.5.11 Fracture-filling minerals

Initial value

At Aberg, the fracture system is divided into four fracture sets with steeply-dipping fractures in west-northwesterly, north-northwesterly and north-southerly directions, plus a low-dipping fracture system. The fracture walls are often stained red by earlier hydrothermal solutions. Mineral fillings consist mainly of calcite and chlorite that are present in all fracture sets, but quartz, epidote, fluorite, haematite/FeOOH, adularia and pyrite also occur. Clay minerals of illite, smectite and mixed-layer occur in smaller amounts in fractures and fracture zones.

At Beberg, northeasterly fractures are most frequent. The fracture walls, which are often stained red due to earlier hydrothermal solutions, are filled with iron-rich prehnite. The northwesterly fracture set is older than the northeasterly one. It was formed by reactivation of early plastic structures and exhibits the longest fractures in the area. The core from zone 1 (Brändan) is characterized by altered, reddish granodiorite with fracture fillings of iron hydroxides and haematite.

North-southerly and north-westerly fractures dominate at Ceberg. Horizontal-subhorizontal fractures are more frequent here than at the other sites. The most commonly occurring fracture-filling minerals are calcite, chlorite, laumontite, pyrite and the clay minerals smectite, illite and asphalt. Both fracture zones and dolerite dykes usually contain clay-altered sections.

Uncertainties

Experience from the tunnel and more recent drilling using the triple tube technique has shown that the fraction of loosely adhering materials (including clay minerals) in the fractures at Aberg has been underestimated in the mapping of conventionally drilled drill cores, since this material has then been flushed away. An underestimate of the fraction of loose material in the fractures means, for example, that the quantity of material that can sorb and retard nuclides is greater than is calculated based on the conventional drill cores. This may be the case at Beberg and Ceberg as well, where only conventionally drilled cores are available. Nevertheless, the retardation resulting from sorption on the fracture-filling minerals is neglected in the safety assessment.

6.5.12 Groundwater composition

The hydrogeochemical description of the three sites is summarized by Laaksoharju et al /1998/. The composition of the natural, undisturbed groundwater is represented by samples taken from four boreholes: one from Aberg, two from Beberg and one from Ceberg. The samples provide good coverage of the different types of groundwater composition that have been measured at other places in Sweden. The chemical compositions of the reference water samples are shown in detail in the tables in section 8.9.2, where the long-term evolution of the groundwater composition is discussed.

The reference water sample from Aberg indicates a saline, lime-poor and sulphate-rich water. The chloride distribution can be attributed to a complex mixture of waters of different origins. The reference water samples from Beberg show both a saline, lime-poor and sulphate-rich water (BFI01), and a lime-rich, chloride- and sulphate-poor fresh water. The reference water samples from Ceberg indicate a lime-poor and sulphate-poor fresh water.

Immediately after construction of the repository, the chemical composition of the groundwater will be affected by engineering and stray materials from the building work and by oxygen that entered the repository while it was open. This is further discussed in the base scenario, section 8.9.2.

Uncertainties

The uncertainties in the hydrogeochemical description include both measurement uncertainties and sampling errors, as well as the representativeness and spatial variability of the water samples.

According to Laaksoharju et al /1998/, the reference water samples represent a typical water from repository depth (500 ± 100 m) at each site. The different groundwater samples from the sites have widely varying compositions, with saline, lime-poor and sulphate-rich water in Aberg, chloride- and sulphate-poor and lime-rich water in Beberg, and lime- and sulphate-poor water in Ceberg.

According to the Data Report, it is reasonable to assume that the uncertainty in groundwater composition, with regard to both its spatial variations and its future evolution, is largely limited by the variation between the compositions of the four reference groundwaters.

6.5.13 Gas composition

Occurrences of gas are discussed briefly in section 8.9.2, "Long-term evolution of groundwater composition".

6.5.14 Engineering and stray materials

Initial value

Stray or foreign materials will be brought down into the deep repository during construction. Furthermore, various temporary and sometimes permanent structures of e.g. concrete and steel are built during the operating period, entailing further entry of foreign materials. Before canister deposition begins, as much of this material as possible that is not needed for stability or safety purposes will be removed.

The quantities of stray materials introduced during the construction and operating periods have been estimated by Larsson et al /1997/. With the aid of this analysis and assumptions concerning the chemical composition of the foreign materials, Jones et al /1999/ have made a compilation of the quantities of different specific substances in the repository, Table 6-10. An assessment of the influence of these substances on the safety of the repository has also been done. The quantity of foreign substances is compared with their occurrence in materials naturally present in the repository, i.e. canister, buffer material, backfill material and substances dissolved in the groundwater.

Table 6-10. Estimated maximum quantities of substances from foreign materials in different parts of the repository. Deposition hole refers to canister and buffer, canister position refers to deposition hole and 6 m of deposition tunnel, gallery refers to 40 m tunnel length in the tunnel from which the deposition tunnels branch off.

Substance	Deposition hole (kg)	Canister position (kg)	Gallery (kg)
Carbohydrates	1.5	4.5	940
Hydrocarbons	15	35	940
Surfactants	1	2.5	50
Nitrogen	0.19	0.48	86
Sulphur	0.06	0.18	13
Phosphate	0.06	0.22	35
K_2O	6.7	22	390
CaO	730	2,400	41,000
Na_2O	1.3	4.8	80
FeO	1	1.5	450
Fe_2O_3	53	175	3,000
SiO_2	250	850	14,500
Al_2O_3	41	140	2,300
Metals	67	430	7,300

Uncertainties

The uncertainties in the estimates of stray materials are great. Jones et al /1999/ conclude that the relative quantities of foreign materials introduced during construction and operation are very small compared with the quantities introduced with buffer and backfill material. The uncertainties are therefore of little importance for the safety assessment.

An exception is the presence of calcium in the deposition holes. If the bottoms of the holes are paved with concrete, the quantity of calcium in the deposition holes can, under certain assumptions concerning the thickness of the concrete pad, be doubled relative to the calcium content of the buffer material.

6.6 Biosphere

Summarizing descriptions of the biosphere at Aberg, Beberg and Ceberg are given in the following. A complete description is provided in Lindborg and Schüldt /1998/, unless otherwise specified in the text.

6.6.1 Aberg

Topography, bodies of water and land types: Aberg is located in the coastal region with surrounding archipelago. The topographical relief varies from –21 to +14 metres above sea level and is characterized as a fissure valley landscape. A large part of the area has open water surfaces and the bays between islands. Runoff takes place mainly to these bays. The land surface has a high proportion of outcrops, and the deposits in the depressions are thin (0–5 m). The deposits are dominated by wave-washed bouldery till that is sometimes overlain by thin sand and clay strata. In the coastal bays, the till is overlain with mud deposits. There is no modern map of the quarternary deposits in Aberg.

Dominant ecosystems: The open water surfaces in the inter-island bays constitute a large portion of the total area. In Aberg's model area, roughly half of the total area is water. The ground vegetation in Aberg is dominated by forestland, which constitutes approximately 40 percent in Aberg's model area.

The aquatic ecosystems in Aberg consist of shallow inter-island bays rich in vegetation (reeds) and soft sediment bottoms which run close to the surface, where occasional rock outcrops occur. Owing to the low salinity, freshwater vegetation probably dominates, the fauna in the bays is probably dominated by freshwater animals with various insect larvae in the sediments. There may possibly be populations of Baltic Sea mussels in the soft bottoms. The fish population probably consists solely of freshwater fishes such as perch and pike.

The forest is dominated by pine trees, interspersed with oaks and other deciduous trees. The undergrowth is often grass where there is a soil cover. The forest has low productivity and the rotation period is long, about 100 years.

Open land such as agricultural land or meadowland comprises approximately 7 percent of the land area in the region. Meadowland and pastureland comprise most of the open land. Since agriculture and cattle grazing have declined sharply in recent years, former agricultural land, meadowland and pastures are being invaded by shrubs.

Wetlands cover a large portion of the land surface, but generally consist of small fens and bogs surrounded by thick deciduous vegetation, such as alder.

The fauna is somewhat more species-rich than on the other sites, owing to the blend of terrestrial and aquatic ecosystems, but relatively little game is taken in the area.

6.6.2 Beberg

Topography, bodies of water and land types: Beberg is located more than 10 km from the coast. The site is flat and the topographical relief varies between 20 and 44 metres above sea level. The southwestern part of the site borders on a large lake, Finnsjön, and there are some minor streams in the area. The site is situated in the drainage basin of the Forsmarksån river. It has been well investigated and a modern soil map is available. The site is located below the highest coastline and has wave-washed till overlain with sand strata in the depressions. The thickness of the deposits is at most 5 m. There are glaciofluvial deposits in the central parts and glacial clay in depressions which is covered by sand or peatland. The ground is partially covered with peat up to 4 metres thick. Outcrops comprise about 15 percent of the surface area. There are lots of lime-containing boulders and deposits carried by the ice sheet from the Bothnian Sea.

Dominant ecosystems: Forestland dominates the total area in Beberg. In the model area it comprises about 60 percent, compared with 25 percent agricultural land and 15 percent peatland. In the whole region, lakes occupy about 10 percent of the total area.

The forest is dominated by pine trees, but there are also many spruce trees and some deciduous trees. The undergrowth consists of alternating bilberry and lingonberry plants on outcropping bedrock and wetlands. The undergrowth is occasionally species-rich due to the lime-rich deposits in the area. Logging results in large clear-cut areas and many young trees. The rotation period is about 85 years with a good yield.

More than half of the **open land** is cultivated, while the rest is meadowland and pastureland. During the past 50 years, approximately one-third of the cultivated land has reverted to meadowland in the region. Less productive meadowland has been planted with forest.

The wetlands in the area consist of extensive fens, bogs and quagmires. Many are lime-rich with rich fen vegetation. Many wetlands have been drained by ditching in recent centuries for crop cultivation and grazing.

The lakes and streams bordering on the site are moderately eutrophic brown waters and have good fish production of ordinary lake species. The lakes and streams have been subjected to extensive regulation schemes in recent centuries /Brunberg and Blomqvist, 1998/.

The fauna is plentiful in the area with many bird species. More game is taken in this area than on any of the sites, for example 100 kg of moose meat per km^2.

6.6.3 Ceberg

Topography, bodies of water and land types: Ceberg is situated more than 5 km from the coast. The area lies in hilly terrain with a topographical relief of between 80 and 130 metres above sea level. The area is drained by two rivers and there are three small lakes. The area has been well-investigated and detailed studies have been conducted at several places, although there is no modern soil map. The area is situated below the highest coastline, and the deposits are dominated by wave-washed till overlain by sand and mo silt in the depressions. Large areas are covered by extensive peatlands. Two large peat bogs are located in the eastern part of the area, with a thickness of between 1.5 and 4.5 m. Besides peatlands, there are podzol soils. The western portions of the area have a great deal of outcropping bedrock where the depressions are covered by wetlands.

Dominant ecosystems: Forestland is the dominant ecosystem in the region, covering 75 percent of the surface. Open land, lakes and wetlands are evenly distributed over the rest of the surface. Peatlands dominate slightly (48 percent) over forest (41 percent) in the model area, while agricultural land covers about 4 percent of the surface and watercourses about 8 percent.

The forest is dominated by coniferous species, consisting of equal parts pine and spruce, plus a smaller portion of deciduous trees (15 percent). The productivity of the forest is moderate and the rotation period is about 90 years. The undergrowth consists largely of bilberry plants. Forestry is intensive with large clear-cut areas in the area.

The wetlands consist of two large peat bog areas in the eastern parts and many fens and bogs between wooded areas. Many of the wetlands have been drained to increase forest production. The peat bogs have been drained for peat-cutting. The open land is concentrated around the Gideälven and is used primarily as meadowland.

Salmon and brown trout have been released in the area, and sport fishing is extensive in the Gideälven and Husaån rivers, which have lots of fish. The small lakes in the area are oligotrophic.

The diversity of **animal species** is slightly lower in this area compared with Aberg and Beberg. The amount of game taken is also the lowest among the three areas, for example 40 kg moose meat per km^2.

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7 Choice of scenarios

7.1 Introduction

A scenario is defined as the sequence of events undergone by the repository system given an initial state and specified conditions in the surroundings. Together, the chosen scenarios should provide reasonable coverage of the various evolutions the repository and its surroundings could conceivably undergo.

The scenarios chosen for SR 97 are:

- A base scenario where the repository is imagined to be built according to specification and where present-day conditions are assumed to exist.
- A canister defect scenario which differs from the base scenario in that a few canisters are assumed to have initial defects.
- A climate scenario that deals with future climate-induced changes.
- A tectonics/earthquake scenario.
- A collective scenario that deals with future human actions that could conceivably affect the deep repository.

Figure 7-1 is a schematic illustration of the different scenarios. The premises for the scenarios are described in section 7.2 and in greater detail in the different chapters (8–12) where the chosen scenarios are analyzed.

The choice is an expert assessment of which initial and ambient conditions are important to analyze in a safety assessment. The choice of scenarios in SR 97 is based on the system description and experience from previous work. The completeness of the choice of scenarios is discussed in section 7.3 below.

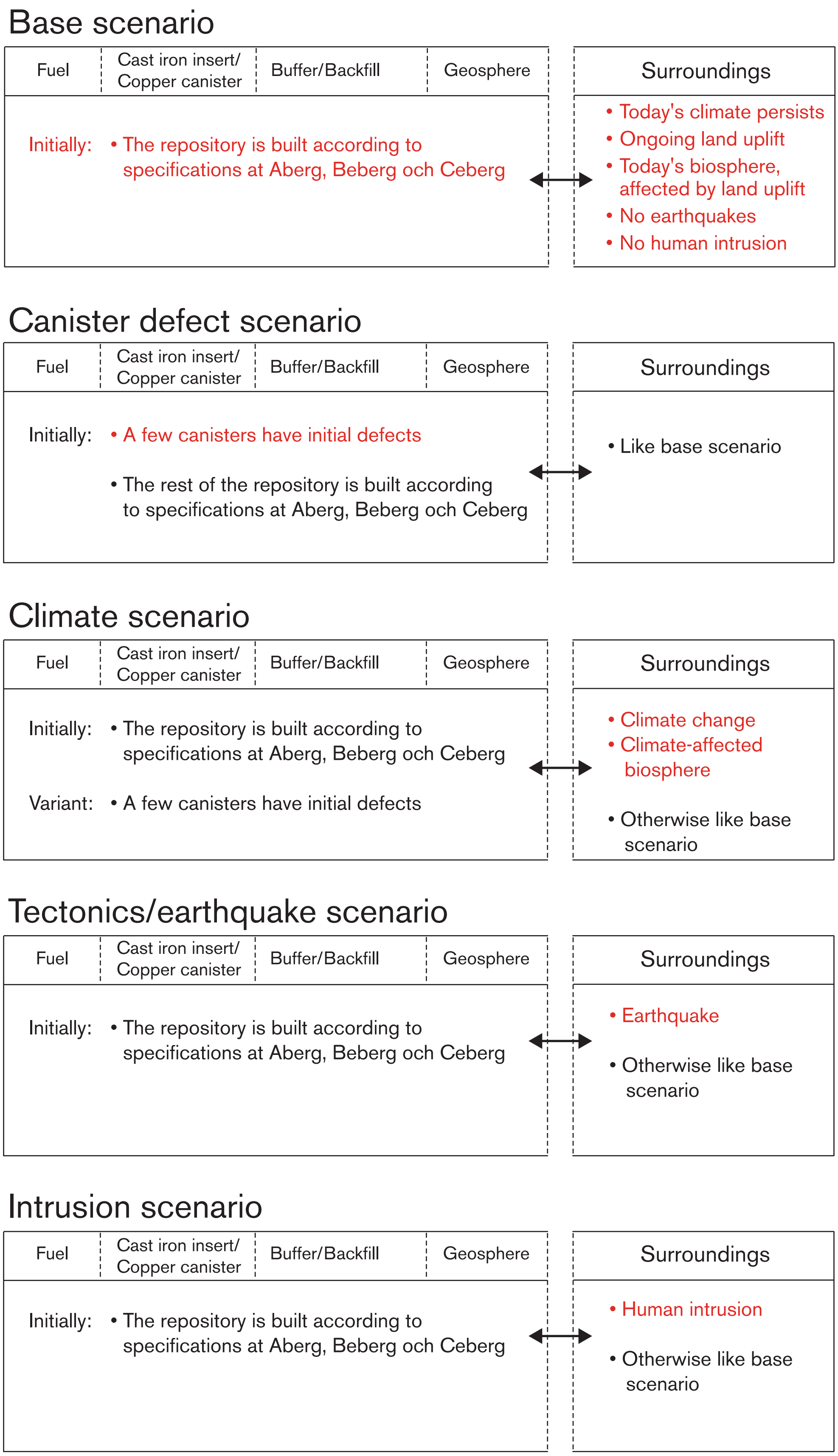

Figure 7-1. *The different scenarios in SR 97.*

7.2 Premises for chosen scenarios

7.2.1 Base scenario

The initial state postulated for the base scenario is that all canisters are fabricated and sealed without defects. The repository is otherwise built according to specifications as per the description in Chapter 6.

The following is assumed for the surroundings:

- Today's climatic conditions are assumed to prevail in the future as well.
- Land uplift and its influence on the biosphere in particular is included in the base scenario. The influence of groundwater flow is discussed in general terms.
- Today's site-specific biospheres are assumed to persist, in addition to the effects land uplift has on the biosphere.
- Rock-mechanical changes take place only as a consequence of aseismic processes, i.e. earthquakes are not included in the base scenario.
- There are no human intrusions.

In SR 97, the base scenario is a ground for comparison for other scenarios. Today's climate is assumed to prevail, even though it is known that the climate is undergoing long-term change. Another possibility would be to include future climate changes in the base scenario in order to achieve a more realistic ground for comparison. This has not been done in SR 97 for the following reasons:

- Scientists and experts do not agree today on what climate changes can be expected. This goes beyond the debated greenhouse effect and includes uncertainty in predictions of the timing and above all the extent of future periods of colder climate.
- It is relatively simple to describe the influence of today's climate on the repository system. This puts the focus of the base scenario on the internal evolution of the repository. This results in a gradual build-up of the complexity of the analysis of repository evolution: firstly the evolution with simple boundary conditions are analyzed in the base scenario and secondly, more complex boundary conditions are analyzed in the climate scenario. It should be pedagogically enlightening and permit a clearer assessment of which internal and external conditions might disturb repository function after the other scenarios have been analyzed.

Another reason for allowing today's climate to provide the boundary conditions for the base scenario is that SSI's regulations explicitly state that the safety account shall include a case where the biosphere conditions do not change. On the other hand, there is in principle nothing to prevent the inclusion of climate change (or other changes in ambient conditions) in the base scenario.

The base scenario is described and analyzed in Chapter 8.

7.2.2 Canister defect scenario

In the canister defect scenario, the initial state of the repository is assumed to be the same as in the base scenario except that a few canisters are assumed to have initial damages as a result of fabrication defects. The ambient conditions are the same as in the base scenario. The emphasis in the analysis lies on the evolution of the initially damaged canisters, on a detailed description of the hydraulic situation in the geosphere and on calculations of radionuclide transport.

The canister defect scenario is analyzed in Chapter 9, where the probability and scope of initial canister damage is discussed.

7.2.3 Climate scenario

The ambient conditions that occur due to expected climate changes on a timescale of a hundred thousand years are analyzed in the climate scenario. Other conditions are assumed to be the same as for the base scenario. The evolution of the repository is compared with that in the base scenario. Consequences of initial canister damage are analyzed as a comparison with the canister defect scenario.

The climate scenario is described and analyzed in Chapter 10.

7.2.4 Tectonics/earthquake scenario

The effects of seismic changes in the surroundings are discussed in the tectonics/earthquake scenario. Other conditions are assumed to be the same as in the base scenario. The probability of different seismic events and consequences in the form of rock movements around deposition holes are analyzed in the scenario.

The scenario is described and analyzed in Chapter 11.

7.2.5 Scenarios based on human actions

The list of human actions that influence the conditions on a repository site can be made almost infinitely long. Since the future development of human society is basically unpredictable, it can never be made complete. The safety assessment covers only:

- actions that affect the performance and safety of the repository system and that can lead to radiological consequences,
- actions that are performed without knowledge of the repository and/or its function and purpose, i.e. inadvertent actions.

Initial state and other ambient conditions are assumed to be the same as for the base scenario. As far as influence on radionuclide transport is concerned, the same premises are assumed to apply as in the canister defect scenario.

The scenario is described and analyzed in Chapter 12.

7.3 Completeness/coverage in choice of scenarios

Just as it is not possible to prove that the system description is complete (see section 5.8), it is impossible to prove that all states in the surroundings that could affect the repository have been identified. Confidence must instead be established in the fact that the scenarios together provide sufficient coverage for a fair assessment of the safety of the repository.

Important measures for achieving completeness in the choice of scenarios are to:

- determine for each process in the system description whether it can be influenced by the initial state or the external surroundings,
- judge for each variable in the system description whether uncertainties in the initial value warrant the choice of specific scenarios or variants,
- systematically document the ambient conditions that have been identified over time as being important for repository evolution,
- compare with databases established by other organizations and in international cooperation.

The choice of scenarios in SR 97 is in principal based on all these points. The choice of scenarios is based on the system description and experience from previous safety assessments by SKB and other organizations.

7.3.1 Analysis based on system description

As was mentioned in Chapter 4, the system description has been developed during the work with SR 97 and has therefore not been able to be fully utilized for a new, systematic choice of scenarios. The description has been used to systematize the descriptions of the initial state as a set of variables and interactions with the system's surroundings under different conditions in the form of THMC interactions. In the Process Report, each process description concludes with a description of how the process ought to be handled in four of the five scenarios analyzed in SR 97. In this way, the influence of these scenarios is analyzed qualitatively in a consistent manner.

There are uncertainties in the description of the initial state as well which should be covered by the choice of scenarios. The initial state is described in SR 97 by a series of variables for the four subsystems **fuel**, **canister**, **buffer/backfill** and **geosphere**. A general review of the uncertainties has given the following results:

- **Fuel:** No uncertainties in the initial state have been judged to be so essential for the outcome that they should be handled in a scenario of their own. Uncertainties in e.g. radionuclide inventory and decay heat can, if necessary, be analyzed as variants of the base scenario (thermal evolution) and the canister defect scenario (radionuclide transport).
- **Canister:** The uncertainties pertain above all to initial integrity. This is handled by analyzing the effects of initial damage in a separate scenario.

- **Buffer and backfill:** No uncertainties in the initial state have been judged to be so essential that they are handled in scenarios of their own. SR 97 does not cover analysis of accidents in fabrication or deposition of buffer. It should be possible to avoid such "buffer defects" by means of suitable inspection procedures in connection with fabrication or deposition of the buffer. Furthermore, the effects are judged to be of much lower dignity than those of initial canister damage. If it should nevertheless be decided in future assessments to study the consequences of "buffer defects", this can suitably be done as a variation within the base scenario.
- **Backfill:** The backfill material must be adapted to the hydrogeochemical conditions on the repository site, above all the salinity. No site-specific adaptation, and therefore no site-specific description of the initial state of the backfill, has been done in SR 97. The analyses of post-closure evolution and performance of the backfill are sometimes simplified. Uncertainties in the initial state of the backfill can, if necessary, be analyzed as variations within the base scenario in future safety assessments.
- **Geosphere:** There are great uncertainties regarding the fracture structure and the spatial distribution of hydraulic properties in both fracture zones and the rock mass in the initial state. The uncertainties are of importance e.g. to the analysis of radionuclide transport in the canister defect scenario. The uncertainties are handled by studying a number of variants in the detailed hydraulic analyses of the geosphere in the canister defect scenario.

The systematic description of the initial state with uncertainties in SR 97 comprises a basis for a possible revision of the choice of scenarios and variants in future assessments.

7.3.2 Systematic documentation of features, events and processes

A description of what ambient conditions can affect the final repository has always comprised a part of the safety assessments performed by SKB. In an early joint project between SKB and SKI /Andersson et al, 1989/, different features, events and processes that could affect the repository were documented. The database was compiled with the assistance of a large number of national and international experts. SKB has since developed its database (see section 4.2.4), for example in conjunction with the development of the interaction matrices /Pers et al, 1999/.

Most features, events and processes in SKB's database are included directly in the system description. Those that are not included can as a rule be classified under one of the different scenarios chosen for SR 97. However, certain more extreme events have been immediately designated as candidates for further analysis. Such events include meteorite impacts and direct hits with nuclear weapons. Analysis of these events is omitted partly because they are highly improbable and partly because their consequences are not significantly influenced by whether or not a deep repository is located under the point of impact.

7.3.3 Comparisons with other organizations

The OECD Nuclear Energy Agency has collected an international database /NEA, 1999/ with results from organizations the world over. SKB's database has also been utilized in producing this database. A general review of the contents of the NEA database reveals that relevant events and processes in the surroundings are included in the scenarios for SR 97. However, no systematic and formal verification of this has been performed. According to below, however, it is unlikely that such an analysis would turn up any important new information.

The scenario analysis in the Finnish safety assessment TVO-92 /Vieno et al, 1992/ has been checked against the contents of SKI's and SKB's different FEP databases by Andersson and King-Clayton /1996/. The scenario analysis in the most recent Finnish safety assessment TILA-99 /Vieno and Nordman, 1999/ has been checked against the OECD/NEA's international database by Vieno and Nordman /1997/ without any essential new information emerging. The scenarios chosen for SR 97 are at least as comprehensive as the scenarios analyzed in the Finnish safety assessments, although no formal verification that all features, events and processes analyzed in the Finnish studies are also covered in SR 97 has been performed.

SKI's performance assessment SITE-94 /SKI, 1996/ has a classification of scenarios that is similar in many respects to that chosen for SR 97. A "reference case" is chosen in SITE-94 whose definition is similar to that chosen for the base scenario and the canister defect scenario in SR 97. The central scenario in SITE-94 exhibits great similarities with the climate scenario in SR 97. Beyond this, SITE-94 discusses in general terms the scenario classes repository closure, seismic effects, alternative climates and various human impacts on the surroundings. The effects of an incompletely closed repository are not analyzed in SR 97, but otherwise the scenario analysis in SR 97 covers those in SITE-94. However, no formal verification has been performed to make sure that all features, events and processes analyzed in SITE-94 are also included in SR 97.

The Swiss safety assessment Kristallin-I /Nagra, 1994/ does not contain any essentially different scenarios from those chosen for SR 97. The same applies to a scenario analysis recently performed in Great Britain by UK Nirex /Billington and Bailey, 1998/. Again, no formal verification has been performed to ensure that all features, events and processes analyzed in these studies are also covered in SR 97.

7.3.4 Future work

For future assessments, a revision of the choice of scenarios is planned with a stringent review of e.g. the initial state and available databases, including the OECD/NEA's international database.

7.3.5 Conclusion

SKB believes that the chosen scenarios provide good coverage of future evolutionary pathways for the deep repository. Nevertheless, the choice of scenarios and variants in future assessment may be modified as more knowledge and experience are acquired.

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8 Base scenario

8.1 Introduction

The base scenario describes the expected course of events (evolution) for the case where the repository is built according to specifications and the conditions in the surroundings are assumed to be in principle constant and the same as today's. All canisters are assumed to be without initial defects, and today's climate persists in the future as well.

Based on previous safety assessments, the canisters can be expected to last for a very long time given these premises. Radionuclide transport should therefore not have to be dealt with in the base scenario. However, this is not a premise, but must be demonstrated by means of the analyses performed for the scenario.

The overall purpose in the base scenario is to study the isolating function of the canister. A fundamental safety criterion for the repository system is that the canisters' copper shells shall remain unbreached. If this criterion is met, it alone is sufficient to demonstrate safety. Several other criteria, for example that the groundwater should be oxygen-free and that the buffer should have low hydraulic conductivity, can be "derived" from the integrity criterion and the intended functions of the barrier system according to section 5.7. The task in the base scenario can be said to be to demonstrate whether the integrity criterion and other auxiliary criteria are met.

8.2 Initial state

The initial state is assumed to be that described in Chapter 6, with the important addition that all deposited canisters are postulated to be without initial defects.

8.3 Boundary conditions

The evolution that follows from the assumption that present-day site-specific conditions in the surroundings apply in the future as well is explored in the base scenario. Such conditions include e.g. the climate on the site and the appearance of the local biosphere.

Certain changes in the surroundings are nevertheless included in the base scenario to make the situation more realistic. These are changes that can be characterized as "known trends". The ongoing process of land uplift (crustal upwarping, postglacial isostatic rebound) is such an example. Land uplift is an effect of the most recent ice age. Another, more long-term known trend is the tectonic evolution, i.e. long-term and large-scale mechanical changes in the bedrock.

In summary, the following is assumed in the base scenario regarding the repository's surroundings:

- Present-day climatic conditions are assumed to prevail in the future.
- Land uplift and its influence on the biosphere in particular is included in the base scenario. Influence on groundwater flow is discussed summarily.
- Present-day site-specific biospheres are assumed to persist, except for the effects of land uplift on the biosphere.
- Rock-mechanical changes take place only as a result of aseismic processes, i.e. earthquakes are not included in the base scenario.
- No human intrusions occur.

More detailed descriptions of climate and expected biosphere evolution on the three sites are given in the following.

8.3.1 Climate

The climate on the different sites varies between a mild temperate climate in Aberg and a cool temperate snow climate in Ceberg. Beberg lies in the border zone between the two climate regions. All areas are affected by a coastal climate. Important climate data are given in Table 8-1.

8.3.2 Changes of the biosphere

Important changes expected in the base scenario in the biosphere are land uplift, successive infilling of lakes and natural changes in the vegetation, plus groundwater changes due to resaturation of the repository. Changes as a consequence of variations in climate are described under climate scenarios. The salinity of the Baltic Sea may change in the future due to climatic conditions, but also due to altered exchange of water through Öresund (the Sound). This change is disregarded in SR 97.

Future land uplift can be predicted fairly well /Påsse, 1997/. Shoreline displacement is a more correct designation of the phenomenon, since it is a composite effect of sea level changes and glacio-isostatic uplift. Shoreline displacement affects the distribution of seawater, lakes and land. It also affects the hydraulic gradient for both near-surface and deeper groundwater flows. Furthermore, former seabeds will gradually become dry and thereby cultivable.

Table 8-1. Some important climate data /Lindborg and Schüldt, 1998/.

	Aberg	Beberg	Ceberg
Annual mean temperature (°C)	7	5.5	2.7
Precipitation (mm/year)	675	670	765
Runoff (mm/year)	150–200	240	345
Percentage snow in precipitation (%)	18	35	33
Mean snow depth (cm)	10	20	30
Snow cover (days/year)	91	110	160
Ground frost depth (cm)	30	50	>100

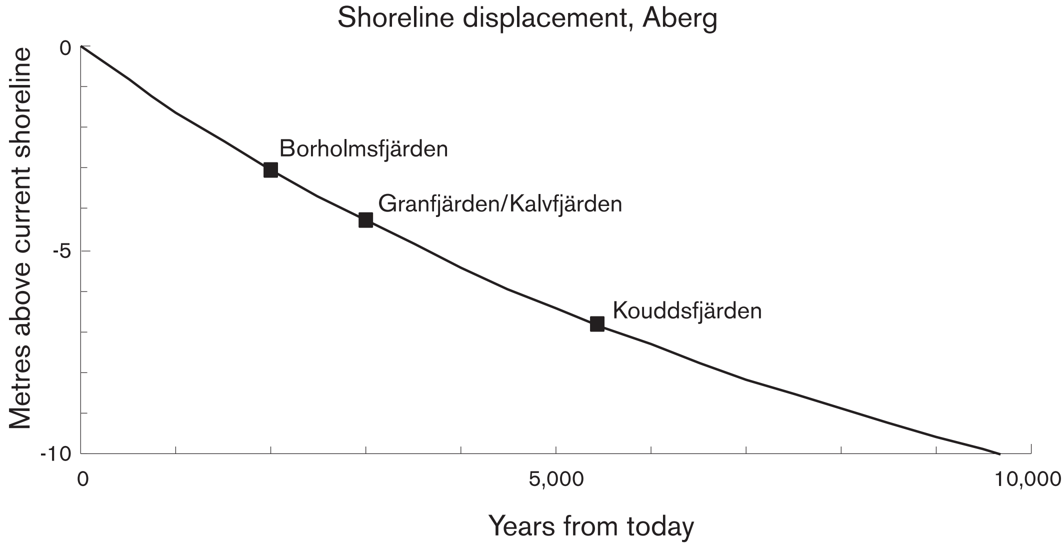

Figure 8-1. *Shoreline displacement in Aberg, based on calculations from Påsse /1997/. The points on the curve show when different bays in Aberg are expected to become isolated from the sea. After 5,000 years the prediction becomes highly uncertain, since glaciation could accelerate the shoreline displacement by lowering the sea level, see further the climate scenario.*

The major vegetation changes that occur are successive infilling of lakes and afforestation of open land. The water composition in the near-surface ecosystems is affected by the transition from seawater to fresh water in connection with land uplift, when sea bays are cut off. A natural acidification and leaching of the soil also takes place.

Aberg is where the most dramatic change occurs, since the site is located on the coast. It is projected that Borholmsfjärden will be isolated and become a lake in about 2,000 years, see Figure 8-1. The lake will probably quickly become a wetland. Gran/Kalvfjärden will become isolated in about 3,000 years, and the outermost bay in about 5,500 years. They will probably be lakes for a long time, since they are relatively deep (21 and 10 m, respectively). When the bays are isolated, they become freshwater environments, which affects the species composition, water composition and potential food path ways.

In **Beberg** and **Ceberg,** land uplift will not affect the surface ecosystems directly, since the coastline is more than 5 km from the sites. Finnsjön Lake in Beberg is, however, expected to form a large wetland in the future. In Ceberg it is likely that the peatlands will be covered with forest.

After closure of the repository, the partially drained rock is refilled with water. The limited areas that may have been affected by the groundwater lowering are then expected to regain groundwater and become more lushly vegetated.

8.4 Overview of processes and dependencies

The initial state of the repository is changed with time by a number of processes that take place in fuel, canister, buffer/backfill and geosphere. The processes can be divided into the categories radiation-related (R), thermal (T), hydraulic (H), mechanical (M) and chemical (C). Figure 8-2 shows a simplified diagram of the system of processes.

Many processes proceed in a parallel and coupled fashion, making the situation appear very complex. However, a closer analysis of the essential couplings in the system clearly reveals main features which greatly simplify the treatment in the safety assessment.

The radiation-related processes – radioactive decay and radiation attenuation – determine what the radiation intensity is in different parts of the repository. They are largely independent of all other processes and can therefore be described first.

After the radiation-related processes have been quantified, the thermal evolution of the repository can be determined in its essential respects. Radioactive decay constitutes the source of the heating, and the further thermal evolution is controlled by heat transport in the different parts of the repository. Heat transport is dependent on the material properties of the repository parts, which are largely constant over long time spans with one important exception: The thermal properties of the buffer are dependent on its water content, which changes during water saturation of the buffer.

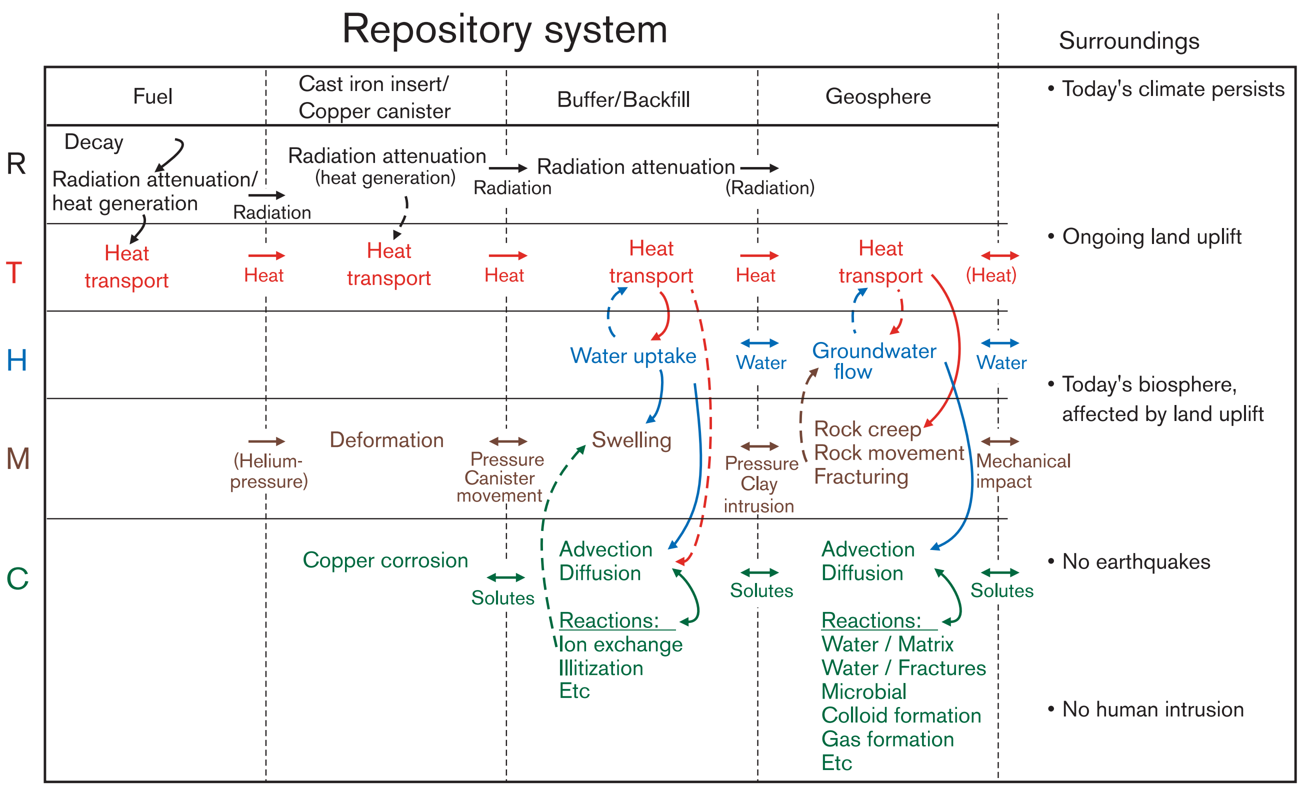

Figure 8-2. Main features of the process system for the base scenario. The strongest couplings are indicated by solid arrows, weaker couplings by dashed arrows. Many couplings judged to have negligible effects have been omitted.

The hydraulic evolution in the base scenario concerns only the buffer and the geosphere, since the interior of the canister and the fuel are hydraulically isolated by the copper shell. The original flow conditions in the geosphere are expected to be restored within a period of up to one hundred years after repository closure. The process of water saturation of the buffer/backfill is dependent on the inflow of groundwater to individual deposition holes and tunnels. Thus, in the case of the buffer there is an interaction with the thermal evolution.

The mechanical evolution of the repository can then be determined. The fuel is mechanically isolated from its surroundings by the cast iron insert. The mechanical evolution is dominated to begin with by swelling of the buffer, which is determined by the buffer's water content, and the thermal expansion of the rock, which is determined by the temperature change in the rock and the composition of the bedrock. Swelling of the buffer gives rise to a mechanical load on both canister and rock. In the long term, the mechanical evolution is controlled by large-scale changes in the geosphere.

Finally, the chemical evolution of the repository can be described. The fuel and the interior of the canister are isolated from their surroundings by the copper shell in chemical respects as well. The chemical evolution is dominated by reaction and transport processes in buffer and geosphere and by corrosion of the outside of the copper canister. The chemical evolution can cause long-term material changes, which can in turn influence the mechanical evolution of the buffer, among other things.

The radiation-related, thermal, hydraulic, mechanical and chemical evolution of the repository are described in that order in the following sections.

8.5 Radiation-related evolution

8.5.1 Overview

The radiation-related evolution describes how the radiation from the radioactive disintegrations in the fuel is spread and attenuated in the different parts of the repository. The energy in the emitted radiation is transformed into heat by attenuation.

Radiation-related processes

The following is a summary from the Process Report of the descriptions of the radiation-related processes of relevance to the base scenario.

The radiation-related evolution in the base scenario includes the processes of radioactive decay in the fuel and radiation attenuation in all subsystems.

The radioactive disintegrations generate α, β, γ and neutron radiation. Most of the α and β radiation is attenuated in the fuel, while the γ and neutron radiation can penetrate out to canister, buffer and rock.

Radiation attenuation and heat generation are most intensive in the fuel, but the process in the cast iron insert also constitutes a significant source of heat in the repository. Radiation attenuation is determined by the geometric dimensions and material composition of the different parts of the repository.

Couplings to other aspects of repository evolution

The radiation-related evolution can be treated independently of the other aspects of repository evolution in the base scenario. This is possible because the radiation-related evolution is not significantly influenced by other processes as long as the copper canister is intact.

Heating in conjunction with radiation attenuation constitutes the heat source in the thermal evolution of the repository. The radiation in the different parts of the repository causes chemical processes such as radiolysis of water and material changes in canister and buffer.

What needs to be shown in the base scenario?

A more detailed description of the following aspects of the radiation-related evolution of the repository is given in coming sections:

- The evolution of the radioactivity and radiotoxicity of the radionuclide inventory in the fuel as a function of time.
- The heat output of the fuel as a function of time as a basis for the thermal evolution.
- A rough quantitative estimate of the intensity of different types of radiation as a function of time in the different parts of the repository. This is needed to be able to estimate the chemical effects of the radiation, which comprise part of the chemical evolution.

Importance for safety

The radiation-related evolution of the repository does not include any processes that have a direct bearing on the isolating capacity of the repository. The radiation does not affect the material properties of the canister or the buffer in the long term. The results are used as input data to other parts of the analysis.

8.5.2 Activity and toxicity

Activity

Figure 8-3 shows how the radioactivity of the fuel changes with time, broken down into fission products and actinides /Hedin, 1997/. As can be seen, the activity is dominated by fission and activation products during the first 100 years, while actinides and actinide daughters dominate after 500 years.

In a long time perspective, as the radioactive substances formed during operation decay, the spent fuel will increasingly come to resemble the mineral that was originally mined to produce the fuel. What will remain will be the naturally occurring uranium isotopes U-238 and U-235 (with half-lives of 4.5 and 0.7 billion years, respectively) and their daughter products. Small quantities of uranium-236 and its daughter nuclide thorium-232 (with half-lives of 23 million years and 14.1 billion years, respectively) and their daughters will also remain for a very long time.

Toxicity

Figure 8-4 shows the radiotoxicity of spent fuel on ingestion via food at different times after operation. The height of the bars is a measure of radiotoxicity, and the graph also shows which elements dominate at different times. All radiotoxicity measures are in

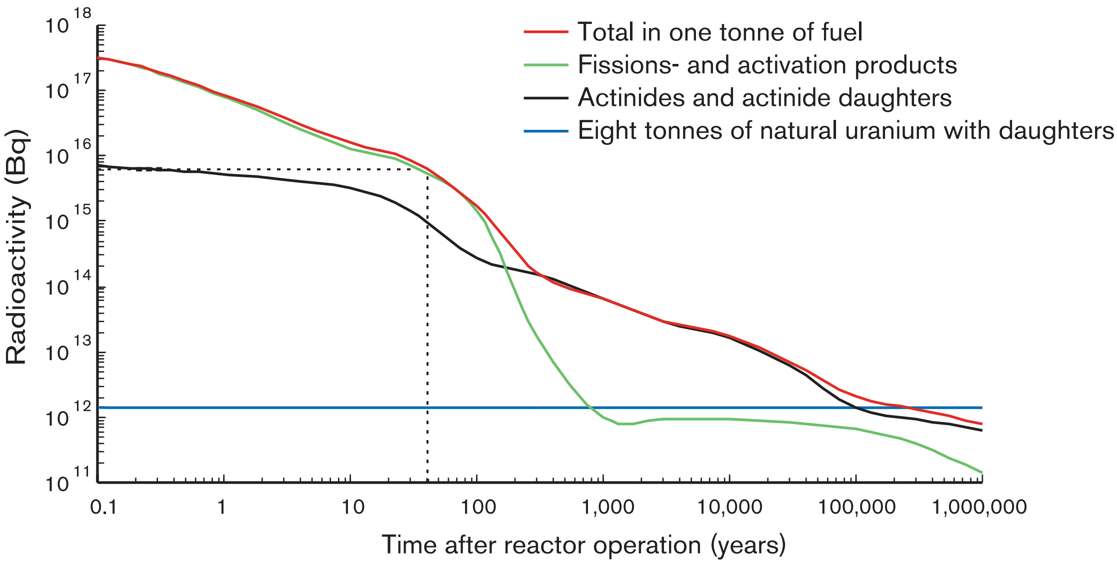

Figure 8-3. *Activity of BWR fuel with a burnup of 38 MWd/kg uranium. The data for the figure are taken from Hedin /1997/ and apply to SVEA-64 fuel. The activity of the reference fuel in SR 97, SVEA 96, with the same burnup, is very similar.*

percent of the total radiotoxicity one month after operation, the first bar in the figure. After 40 years, when the fuel is to be disposed of, and after more than 1,000 years, the radiotoxicity is dominated by Am-241, formed by decay of Pu-241. As short-lived isotopes disappear, the radiotoxicity will be dominated by more long-lived radionuclides. After 10,000 years, for example, nearly half of the radiotoxicity comes from the plutonium isotope Pu-239 with a half-life of 24,000 years. The evolution of radio-toxicity with time is also shown in Figure 3-2, Chapter 1.

8.5.3 Decay heat

The radiation energy that is liberated by the radioactive disintegrations in the fuel is converted into heat. Heat generation in the fuel after operation is called residual power or decay heat. Figure 8-5 shows how the decay heat declines with time /Håkansson, 1999/.

When the fuel is to be emplaced in the deep repository after about 40 years of interim storage, it generates approximately 800 Watts of thermal power per tonne of fuel. The decay heat constitutes the heat source in the thermal evolution of the repository discussed in section 8.6.

8.5.4 Gamma and neutron intensities

Initially the gamma and neutron dose rates are approximately 130,000 and 5 mGy/h, respectively, at a distance of one metre from two tonnes of unshielded fuel (the contents of one canister) /Hedin, 1997/. The intensities then decline according to Figure 8-6. Immediately outside the canister, the equivalent initial values are 350 and 20–40 mGy/h, respectively (neutrons are attenuated very little by the canister). These dose rates also decline as shown in Figure 8-6.

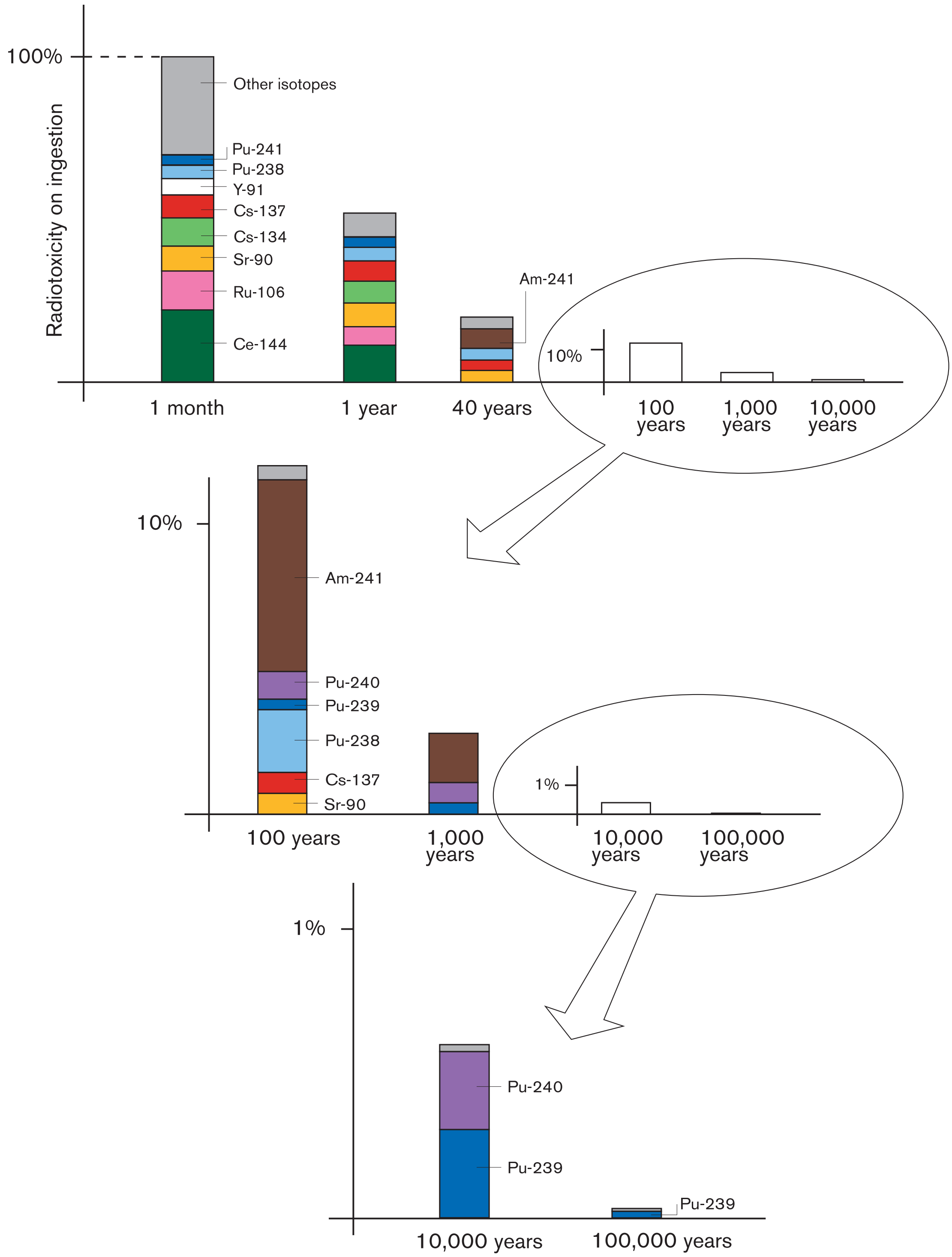

Figure 8-4. *Relative radiotoxicity on ingestion of BWR fuel with a burnup of 38 MWd/kg uranium. The data for the figure are taken from Hedin /1997/ and apply to SVEA-64 fuel. The radiotoxicity of the reference fuel in SR 97, SVEA 96, with the same burnup, is very similar.*

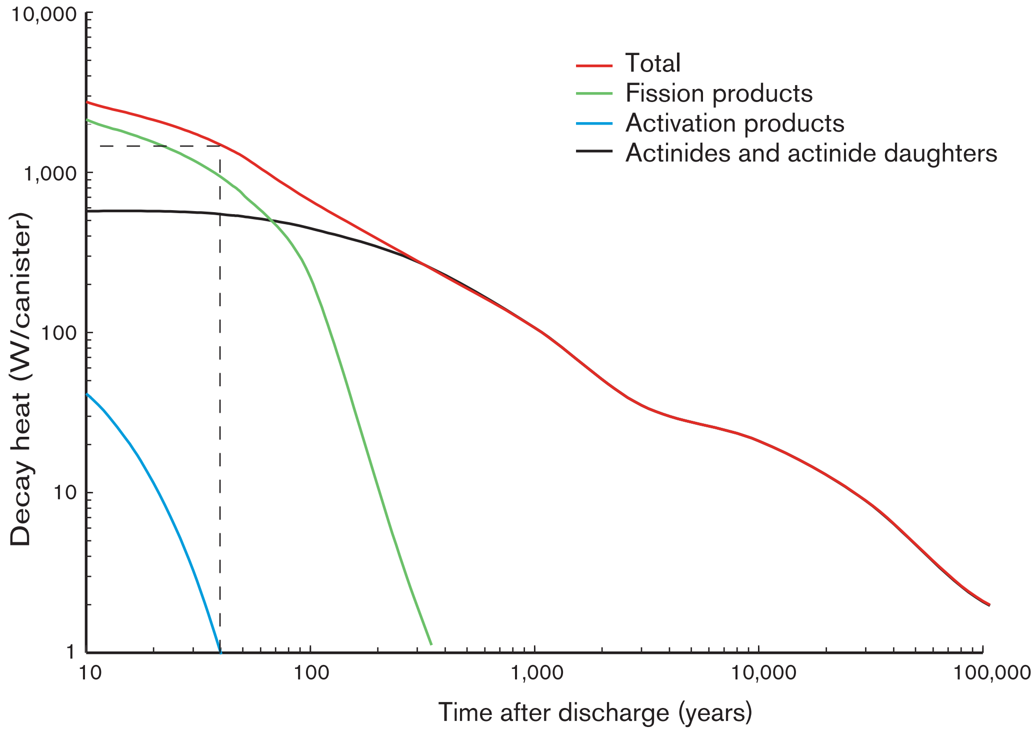

Figure 8-5. *Decay heat as a function of time for the reference fuel SVEA 96 with a burnup of 38 MWd/kg U.*

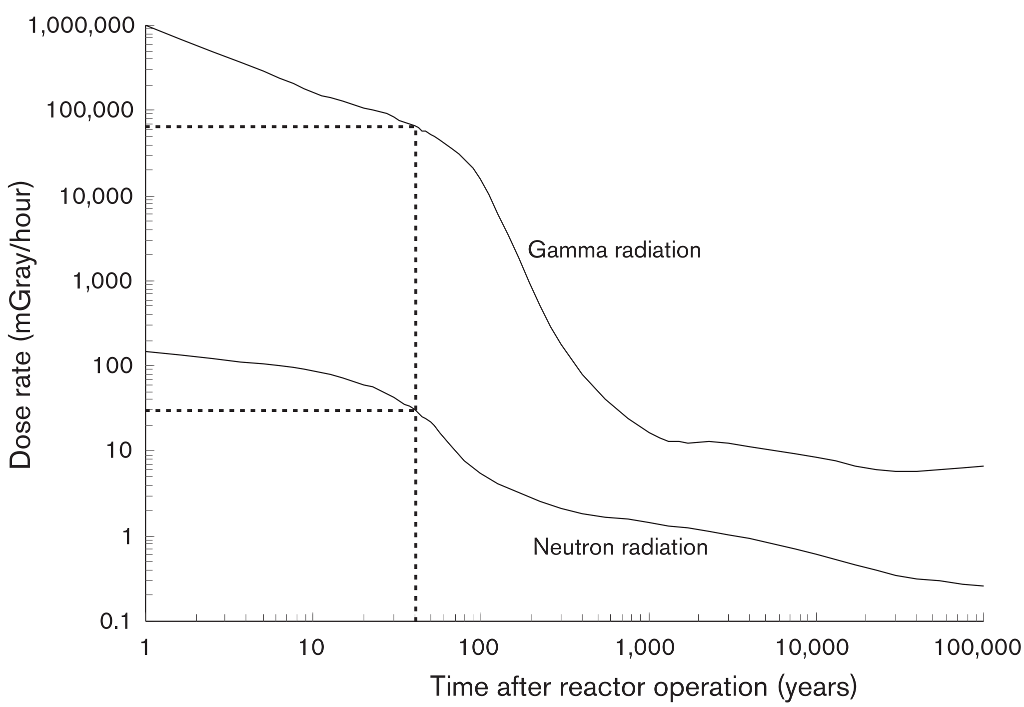

Figure 8-6. *Gamma and neutron dose rates as a function of time at a distance of one metre from two tonnes of unshielded BWR fuel (the contents of one canister). The data for the figure are taken from Hedin /1997/ and apply to SVEA-64 fuel. The dose rates for the reference fuel in SR 97, SVEA 96, with the same burnup, are very similar.*

8.5.5 Confidence

Process understanding

The fundamental processes in the radiation-related evolution of the repository – radioactive decay and radiation attenuation – are well-understood both experimentally and theoretically, see the Process Report.

Models

The evolution of radioactivity, radiotoxicity and decay heat can be calculated analytically when the content of radionuclides at deposition is known. Models for radiation shielding calculation provide a sufficiently detailed treatment of radiation attenuation.

Data

The radiation-related evolution requires decay data and inventories of radionuclides in the fuel, as well as radiation shielding data for the fuel, canister and buffer materials. The quality of available data is fully adequate for the calculations carried out in the base scenario. Uncertainties in the radionuclide inventory are discussed in the Data Report.

8.5.6 Conclusions

The radiation-related evolution has no direct bearing on safety in the base scenario. The calculation results are used in other analyses, particularly in the analysis of the thermal evolution, where the decay heat is used.

The fundamental understanding of the processes involved is good, as is the quality of available models and data.

8.6 Thermal evolution

8.6.1 Overview

Heat is transported in the earth's crust from the internal hot parts of the earth to the surface, where heat is emitted to the atmosphere. Heat from decay in radioactive minerals also contributes significantly to the temperature evolution in the upper bedrock.

The repository introduces a new heat source in the radiation energy that is liberated by the radioactive disintegrations in the fuel and is then converted to thermal energy. The generated heat flows out to canister, buffer and rock, giving rise to a heating process that lasts for thousands of years. A heat wave is propagated in the geosphere and will reach the surface from a repository at a depth of 500 metres a hundred years or so after deposition. The size and velocity of the wave is determined by the heat output of the fuel and the thermal conductivity of the rock.

Thermal processes

Initially, at deposition, the geosphere has a temperature that is site-specific and depth-dependent. The initial temperature of parts of the repository is described in Chapter 6.

The following is a summary from the Process Report of the descriptions of thermal processes that have a bearing on the base scenario.

The thermal evolution of the repository is controlled by the process of heat transport in and between the different parts of the repository. Heat transport can take place by conduction, flow (convection) or radiation. Heat transport within different parts of the repository can often be described accurately, while heat transfer between different parts may be associated with greater uncertainties.

Heat is transported from inside the fuel out. After a short time, a state arises where the temperature evolution of a given part of the repository, for example the canister, is determined by the heat generated in the fuel and the heat transport properties of the repository parts and interfaces located outside (in this case) the canister, i.e. buffer/backfill and geosphere.

In the **fuel**, transport takes place as conduction and the heat conduction properties are well known.

Between the fuel and the cast iron insert, heat is transferred by both heat radiation and conduction. Conduction takes place via residual gases in the fuel and at surfaces where fuel and insert are in direct contact.

In the metal in the **cast iron insert and copper canister**, heat transport takes place by conduction. Between insert and canister, heat is transferred by radiation as well as by conduction in direct contact at the bottom surface. The heat conduction properties of the metals are well known, while the radiation properties of the inner surface of the copper canister, and thereby heat transfer between insert and canister, constitute an uncertainty which influences the thermal evolution in the fuel.

In a **water-saturated buffer**, heat is transported by conduction with well-known heat conduction properties. After swelling, at full water saturation, the buffer stands in direct contact with both canister and rock and heat transmission takes place by conduction.

Heat transport in the **buffer during the saturation process** is more complicated, partly because thermal conductivity is dependent on water content. In the buffer itself, convection can also make a minor contribution to heat transport during this stage, due to the fact that water vapour flows in the buffer. The vapour flow increases the thermal conductivity of the buffer and can therefore be pessimistically disregarded, since the temperature of the canister surface is thereby overestimated.

The heat transfer between canister and buffer becomes more complex because there is a water/gas-filled gap in this interface during the water saturation phase. The gap will be filled out when the buffer swells, but our understanding of this process, and thereby the heat conduction properties in the gap, is associated with uncertainties.

The influence of the **backfill** on the thermal evolution is small, see the Process Report.

In the **geosphere**, heat is mainly transported by conduction. Heat flow with the groundwater makes a negligible contribution. The heat conduction properties of various rock types are well-known. Accuracy in the description of heat transport in the geosphere is instead limited by how well the composition of different rock types in the geosphere can be determined.

Couplings to other aspects of repository evolution

The thermal evolution of the repository is driven by the radiation-related evolution. During the saturation phase in the buffer, there is an interaction with the hydraulic evolution. Otherwise the thermal evolution is more or less independent of other aspects of repository evolution.

The temperature leads to thermal expansion in all parts of the repository. This is above all of importance for the mechanical evolution of the geosphere. The temperature is also of importance for all chemical reactions.

What needs to be shown in the base scenario?

A more detailed description of the following aspects of the thermal evolution of the repository is given in coming sections:

- Calculations for individual deposition holes in Aberg, Beberg and Ceberg. Among other things, the maximum temperature on the canister surface is given, which may not exceed 100ºC. The criterion that the temperature in the buffer should not exceed 100ºC in order to avoid mineral alterations (illitization) is thereby also satisfied.
- Calculations of the temperature in the entire repository in Aberg, Beberg and Ceberg as input data to the description of the hydraulic, mechanical and chemical processes that are dependent on the temperature. Moreover, the thermal impact on the ground surface above the repository needs to be estimated.

The thermal evolution in fuel and canister is not calculated in SR 97. In the Process Report, calculations are cited where the surface temperature on the fuel rods can be up to approximately 400ºC at deposition with pessimistic assumptions. As long as the copper canister is intact, the temperature distribution in the interior of the canister has no bearing on the thermal evolution in the base scenario.

Importance for safety

The thermal evolution of the repository does not include any processes that have a direct bearing on the isolating capacity of the repository. The results are used in the mechanical and chemical analyses.

8.6.2 Thermal evolution in buffer and geosphere

Calculations of the thermal evolution in buffer and geosphere are presented in this section. The Process Report contains a detailed description of the thermal processes in the different parts of the repository. The text in this section is a summary of Ageskog and Jansson /1999/.

The analysis of the thermal evolution in buffer and geosphere should give the temperature as a function of time and space in the two subsystems. The temperatures are used as a basis for analyzing the temperature-dependent mechanical and chemical processes in particular.

Another important purpose of the calculations is to check that the temperature on the surface of the canister does not exceed 100ºC. This criterion is set to avoid boiling on the canister surface /Werme, 1998/. Boiling could lead to enrichment of salts on the surface, which could in turn cause corrosion effects that are difficult to analyze.

Premises

Fuel quantities: Approximately 8,000 tonnes of fuel are assumed to be disposed of on each of the three sites, see further under "geosphere data" below.

Canister data: In the thermal evolution of the repository, a quasi-steady state is achieved within a few weeks of deposition where the heat flow through canister and buffer is determined by the fuel's heat output. It is therefore only the heat flow from the canister that is of interest for the temperature calculations in buffer and geosphere. The flow from the canister is dependent on the quantity and burnup of the fuel it has been filled with. With adjustments of interim storage period and deposition sequence, the same heat flow can be obtained for all canisters even if the operating period varies between 25 and 40 years. In this study, an initial output of 1,625 W per canister and a site-adapted deposition sequence are assumed. This corresponds to an average interim storage period of approximately 30 years.

Heat conduction between canister and buffer: At canister deposition there is a centimetre-wide gap between canister and buffer. The gap is filled at deposition with water, and the swelling buffer will eventually fill out the gap. However, the heat from the canister may expel the water from the gap at an early stage, which is of great importance for the thermal conductivity of the gap and thereby for the temperature on the canister surface /Ageskog and Jansson, 1999/. In the calculations of the maximum temperature on the canister surface below, the gap is pessimistically assumed to remain open.

Buffer data: The thermal conductivity of the buffer is dependent on the degree of saturation. A fully water-saturated buffer has a thermal conductivity of 1.2–1.4 W/(m•K). In SR 97, the buffer blocks are assumed to be deposited with a degree of saturation of 85 percent. After deposition, the heat from the canister will redistribute the water in the buffer within a few months /Börgesson and Hernelind, 1999/ so that the degree of saturation becomes lower nearer the canister. In the modelling, the buffer has been divided up into three concentric layers, where the degree of saturation varies between 70 and 100 percent, which is pessimistically assumed to correspond to thermal conductivities between 0.9 and 1.15 W/(m•K).

The degree of saturation will increase with time as the buffer absorbs water from the host rock. However, it is not unrealistic to assume that the maximum canister temperature is reached before water uptake has become significant. Credit can therefore not be taken for this process in short time perspectives when determining the maximum temperature on the canister surface.

Geosphere data: The site-specific repository layouts in Chapter 6 have been used in the temperature calculations. The tunnel spacing is 40 metres and the spacing between deposition holes is 6 metres in Beberg and Ceberg. This is a preliminary minimum distance that has been chosen for construction-related reasons. In Aberg, the site-specific adaptation gave a canister spacing of 7.5 metres. The canister spacings correspond to a total number of canisters of 3,650, 4,261 and 4,165, respectively, in the tunnel systems

Table 8-2. Thermal properties of the geospere on the three sites /Ageskog och Jansson, 1999/.

	Dominant rock type	Thermal conductivity W/(m · K)	Specific heat capacity $MJ/(m^3 \cdot K)$	Initial temperature °C	Temperature gradient °C/km
Aberg	Diorite	2.8	2.0	16.0	13.5
Beberg	Granite	3.2	2.1	13.5	12.7
Ceberg	Gneiss	3.8	2.3	11.0	15.5

on the three sites. (The total length of the tunnel systems varies between the sites, as thereby does the number of canisters between Beberg and Ceberg.)

The geosphere at Aberg, Beberg and Ceberg is dominated by the rock types diorite, granite and gneiss, respectively. The rock type determines the thermal conductivity and the specific heat capacity. The three sites are located in southern, central and northern Sweden, respectively, which has a bearing on the initial temperature. Table 8-2 contains the site-specific thermal data used in the analysis.

Surface temperature of canister

As noted above, the temperature on the canister surface may not exceed 100°C in order to avoid boiling. To allow for uncertainties in input data, the stricter criterion that the maximum surface temperature may not exceed 90°C is used in the temperature calculations. The gap between canister and buffer is handled by assuming a temperature fall of 10°C between canister surface and buffer, as explained in Ageskog and Jansson /1999/. What is then concretely calculated is the temperature on the buffer's inner boundary, which may thus not exceed 80°C.

Details on the modelling are provided in Ageskog and Jansson /1999/. Figure 8-7 shows the results of the modelling of temperature as a function of time on the inner surface of the buffer deposited at Aberg.

Figure 8-8 shows the temperature as a function of the distance from a canister deposited at Aberg at a number of different post-closure times between 0 and 15 years.

In Ceberg, the decay heat could be increased to approximately 1,850 W per canister with a canister spacing of 6 metres, while in Beberg the decay heat corresponds relatively well to a canister spacing of 6 metres. In Aberg it is the temperature restrictions that determine the canister spacing, so the canister heat output cannot be increased there either.

Heat transport in the geosphere

Heat transport in the geosphere was modelled with simplified assumptions concerning the geometry of the near field. Only the deposition tunnels are represented in the model, without details regarding deposition hole, canister and buffer. The importance of the backfill for the thermal evolution of the geosphere can be neglected, see the Process Report. Here as well, the initial canister output is 1,625 W for all sites.

In the calculation, deposition is assumed to take place in two steps to simulate the planned sequence of progressive repository construction. 400 canisters per year are deposited in stage one and 200 canisters per year in stage two. The starting time for

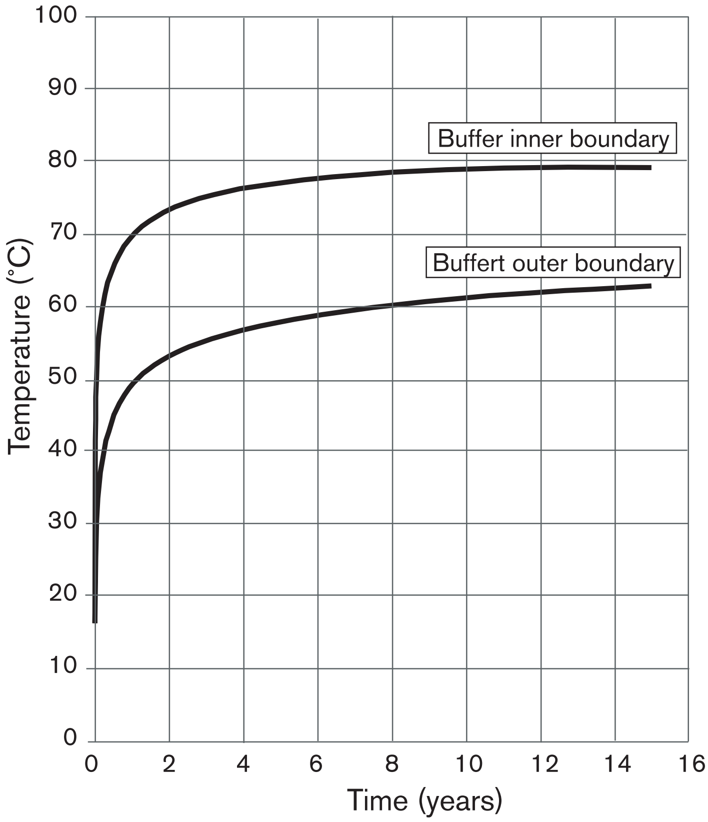

Figure 8-7. Temperature as a function of time on the buffer boundaries at Aberg.

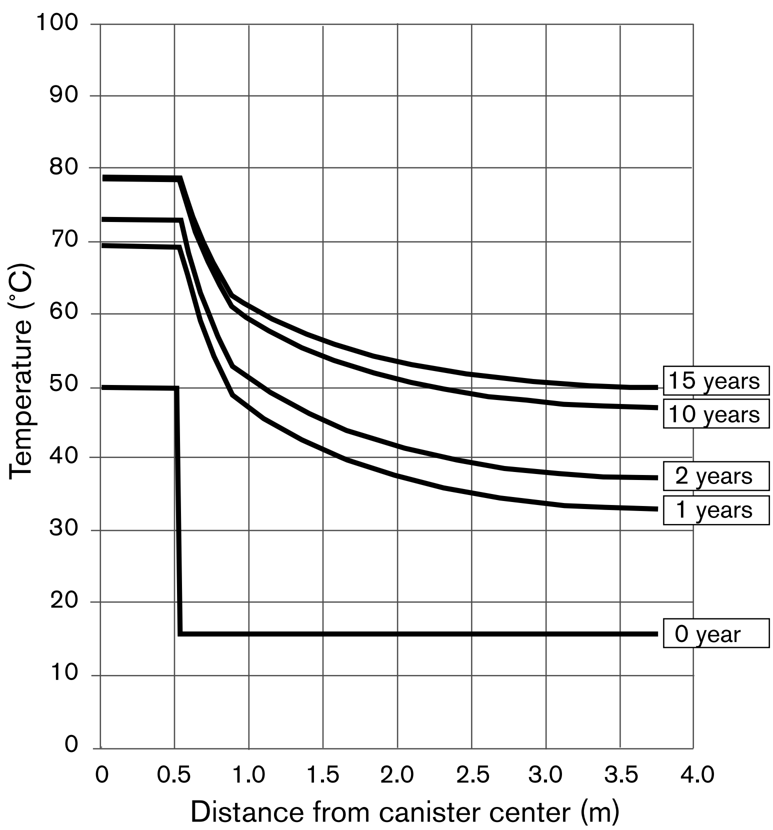

Figure 8-8. Temperature as a function of distance from canister in Aberg.

Table 8-3. Timetable for deposition sequence in temperature calculation.

	Number of canisters in phase one	Number of canisters in phase two	Number of years for phase two
Aberg	400	3,250	16
Beberg	400	3,861	19
Ceberg	400	3,765	19

step two is determined by the quantity of fuel to be disposed of and is different for the different sites. The heat load is increased annually to simulate the actual deposition sequence. Details of the deposition sequence in the calculation are provided in Table 8-3.

Figure 8-9 shows the temperature at a depth of 600 metres in Aberg 15 and 200 years after the start of deposition. Figure 8-10 shows a vertical section of Aberg after 1,000 years.

The temperature at the boundary of the deposition holes reaches a maximum after about 20 years and then amounts to approximately 60, 50 and 45ºC in Aberg, Beberg and Ceberg, respectively. On a larger scale, the maximum temperature is reached when heat waves from different tunnels interfere, and in Aberg when heat from the two repository levels is superimposed. The maximum temperature in the rock blocks between the repository levels in Aberg is about 55ºC and is reached after 450 years. The corresponding temperatures in the repository levels in Beberg and Ceberg are 45 and 40ºC, respectively, and are reached after 90 and 80 years, respectively.

Impact on the surface: Heat from the repository reaches the surface after a few hundred years. The heat will have a marginal impact on the thermal conditions on the ground surface. The effect is comparable to the natural geothermal heat flow, which is in turn less than a tenth of a percent of the heat input of sunshine.

8.6.3 Confidence

Process understanding

The fundamental understanding of different heat transport phenomena is good for both canister, buffer and rock, see the Process Report.

Models

Available models adequately represent heat transport in the different parts of the repository. There are adequate both analytical and numerical models for the geosphere.

Data

The analysis requires data on the decay heat from the fuel (from the radiation-related evolution) as well as thermal and geometric data for canister and buffer. In addition, site-specific thermal data for the geosphere are required. In general, data on heat transfer between different media, e.g. cast iron insert and copper canister or canister and buffer, are more uncertain than heat conduction data within a medium.

Data uncertainties are handled pessimistically in the estimation of the canister's surface temperature. Otherwise the quality of the data is adequate for the calculations required in the base scenario.

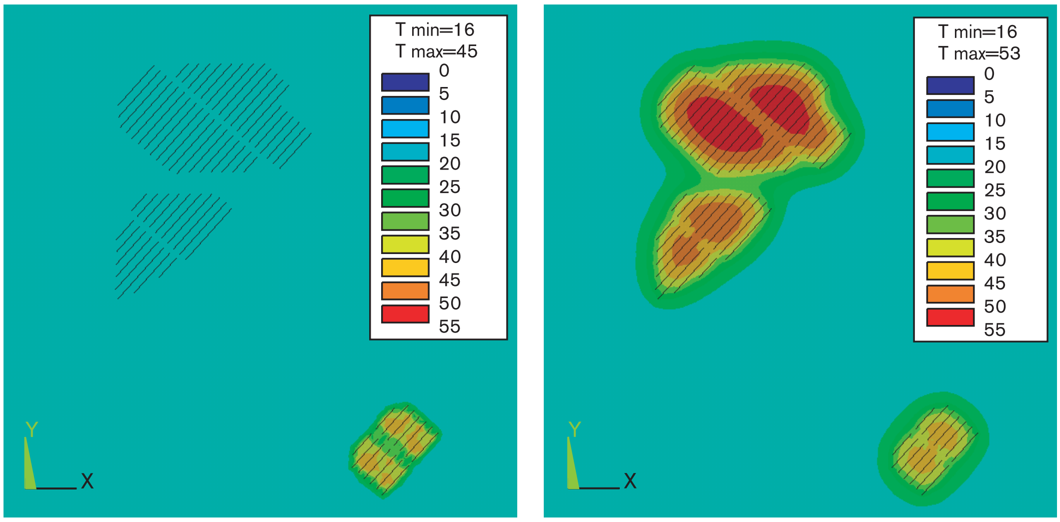

Figure 8-9. *The temperature at a depth of 600 metres in Aberg 15 and 200 years after the start of deposition.*

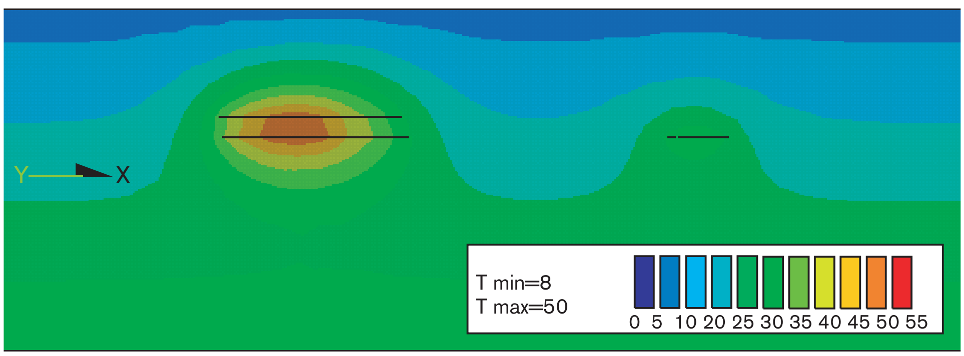

Figure 8-10. *The temperature in a vertical section at Aberg 1,000 years after the start of deposition. The horizontal black lines mark the repository. The top of the figure corresponds to the ground surface.*

8.6.4 Conclusions

The requirement that the surface temperature of the canister may not exceed 100°C can always be met with the necessary safety margin by choosing a suitable spacing between deposition holes or by adjusting the fuel content of the canisters. The requirement is verified by means of standardized temperature calculations where data uncertainties are handled pessimistically.

Calculations of other aspects of the repository's thermal evolution can be conducted with sufficient precision. The results have no direct bearing on safety, but are used above all in the description of the mechanical and the chemical evolution.

8.7 Hydraulic evolution

8.7.1 Overview

The hydraulic evolution in the base scenario concerns only buffer/backfill and geosphere as long as the canister is intact. The canister interior and the fuel are hydraulically isolated by the intact canister.

Initially the geosphere around the repository is partially drained as a consequence of construction and operation. Drainage can cause deeper-lying groundwater, often of higher salinity, to be drawn up to repository depth, a phenomenon known as upconing. Drainage and reversion to original groundwater level proceed as different parts of the repository are built and the repository is backfilled and closed after deposition. Some time after closure, the groundwater level and flow pattern are expected to return to their original state.

Buffer and backfill are partially water-saturated at deposition. After deposition, they will in time become fully saturated with water. How long this takes depends on the water flow around tunnels and deposition holes and is generally expected to be around ten years.

After water saturation, the hydraulic conductivity of the buffer is very low, which contributes to its isolating function in the repository. In the geosphere, a more or less constant flow state is reached after the groundwater has returned to its original level.

Hydraulic processes

The following is a summary from the Process Report of the descriptions of the hydraulic processes that have a bearing on the base scenario.

The dominant hydraulic process in the **geosphere** is groundwater flow. The fundamental driving force for the groundwater flow in the geosphere is pressure and head differences between different points. Ultimately, the flow is driven by precipitation.

In the areas that are being considered for a deep repository, the geosphere has a relatively low permeability to water, which means that the groundwater table will in general follow the topographical variations in the landscape. The differences in groundwater level give rise to differences in potential energy (head) between different points. The groundwater flow strives to equalize the differences, while precipitation constantly “tops up” the groundwater table, and an equilibrium situation for the flow is established. The groundwater flows in the geosphere’s fracture system and eventually runs out into springs or directly into watercourses, lakes or seas.

The flow pattern in the geosphere is determined by the size of the energy differences and by the hydraulic conductivity of the geosphere. Conductivity is determined above all by the fracture structure, which is highly heterogeneous. Knowledge of the fracture structure constitutes the predominant uncertainty in the description of the groundwater flow.

The flow is also affected by variations in salinity and thereby water density between different parts of the geosphere. Salinity usually increases with depth. Salinities can vary in the long run as a consequence of changes stemming from the most recent ice age. Another long-term change that can affect the groundwater flow is the ongoing process of land uplift, which leads among other things to a displacement of the shoreline.

Precipitation/dissolution of fracture minerals can change the hydraulic properties of the fracture system, but this is only expected to have appreciable effects in the event of major climate changes /Process Report/.

The groundwater flow is important to describe in the base scenario, since the groundwater transports dissolved substances and thereby influences the repository's chemical environment.

The hydraulic processes in the geosphere also include gas transport. Gas transport enters into the base scenario primarily because air is transported out when saturation conditions are restored in the geosphere. Any gas remaining after that can dissolve in the groundwater with good margin, and no gas transport is expected. Gas transport is therefore not dealt with explicitly in the base scenario, see further the Process Report.

The two hydraulic processes water transport and gas transport occur in **buffer and backfill**. At deposition, the buffer/backfill is not in hydraulic equilibrium with the surrounding rock. The buffer strives to absorb water until equilibrium is reached. The most important driving forces are the clay mineral's capacity to bind water and osmosis, which together create a negative pressure (suction) relative to the surrounding rock. The process is a complex interaction between, among other things, water flow and the heat flow from the canister through the buffer. In parallel with the water flow, water vapour can also be transported outward from the hotter interior to the outer portions of the buffer, where the vapour condenses.

The pores are eventually filled entirely with water – the buffer/backfill is said to be water-saturated. The hydraulic conditions in the surrounding rock are crucial for how long it takes to attain this state. The buffer swells during the process, and towards the end a swelling pressure arises against the canister and the rock which corresponds to the water-binding capacity of the bentonite. The water in the bentonite and the groundwater in the rock have then achieved a state of equilibrium, and no further water exchange takes place.

The detailed sequence of events in the saturation process is not important to describe in the safety assessment. A description is, however, needed of the state attained in the buffer at saturation, along with an estimate of how long the saturation process takes.

After water saturation the buffer has very low water permeability. Solutes are then transported through the buffer mainly by diffusion.

Gas transport also occurs in the buffer/backfill in the base scenario, above all when trapped air from the deposition phase leaves the repository early on. After that, so little gas is expected to form that it should be able to dissolve in the pore water in the buffer/backfill with ample margin. Transport in the gas phase is therefore not treated further in the base scenario, see further the Process Report.

Couplings to other aspects of repository evolution

There is in the buffer a coupling to the thermal evolution during the water saturation phase. The hydraulic evolution influences the mechanical evolution above all via the swelling of the buffer, and the chemical evolution via advection in the geosphere.

What needs to be shown in the base scenario?

The following are needed in the base scenario:

- a rough description of the site-specific hydraulic evolution in the geosphere, and
- a more detailed description of the hydromechanical evolution when buffer/backfill is saturated with water.

Importance for safety

The hydraulic evolution in the geosphere has an indirect bearing on the canister's isolating capacity, since the groundwater transports solutes and thereby affects chemical processes such as canister corrosion.

The hydraulic evolution of the buffer does not have a direct bearing on the canister's isolating capacity. However, it is important to ensure that the buffer is saturated under any circumstances so that it will function as intended in the repository. Furthermore, it is important to study the build-up of the swelling pressure as the buffer is saturated, among other things so that it is possible to determine what stresses an uneven swelling pressure might entail for the canister.

8.7.2 Hydraulic evolution in the geosphere at Aberg, Beberg and Ceberg

Natural flow situation, drainage and resaturation

The repository area will be partially drained during the construction period, returning to its natural state afterwards when the repository is backfilled.

Practical experience in Swedish bedrock of drainage around different types of underground facilities shows that the extent of the effects is dependent to a high degree on the hydraulic and structural properties of the water-bearing fracture system /Axelsson et al, 1994/. Experience from the Äspö HRL supports this view /Rhén et al, 1997b/.

Cox and Rodwell /1989/ have studied, by means of numerical modelling and analytical calculations, the importance of rock permeability, repository depth and internal gas production for the time for resaturation of the repository level in a deep repository. According to their results, the time for resaturation of the repository level is presumably shortest in Aberg and longest in Ceberg under otherwise similar conditions. A simple rough calculation of the quantity of water entering the Äspö HRL shows that a hypothetical repository on the site would be resaturated in 1–10 years. However, the inflow into a deep repository will probably be restricted in relation to that which occurs now in the Äspö HRL, which would lead to a longer resaturation time. It is assumed in the calculation that half of the open tunnel volume will be filled with inflowing water.

In conjunction with drainage and resaturation, deep-lying saline water may be drawn up to the repository, a phenomenon known as upconing. This is discussed briefly in section 8.9.2 on the chemical evolution of the geosphere.

As the geosphere is resaturated, the flow pattern is expected to return to the original, natural situation that prevailed before the repository was built.

Calculations of regional groundwater flows for undisturbed, natural conditions are summarized below for the three sites. The text is based among other things on hydrogeological descriptions of Aberg, Beberg and Ceberg /Walker et al, 1997/, which are based on a large quantity of data from investigations of the sites. The summary below is brief. A more detailed description of the local flow situation for the sites is presented in Chapter 9 on the canister defect scenario.

In the long term, postglacial land uplift will lead to changes in the natural flow pattern. This is discussed at the end of the section.

Large-scale natural flow situation at Aberg

The region around the site is characterized by low-lying coastal terrain with an elevation difference of around 30 m from sea level to the western part of the area. There are a large number of drainage basins in the terrain, see Figure 8-11. These drainage basins or catchment areas are described more fully in Walker et al /1997/. The regional groundwater table follows the topography, and due to the topographical level differences the regional flow is directed from the highlands in the west towards the coast in the east. Brackish water underlies the fresh surface water in the coastal area.

A 100 km^2 large area is studied in a large-scale flow model for Aberg /Svensson, 1997/. The model includes density-driven flow, where density is dependent on salinity. The model simulates the central hydrological processes in the area such as infiltration, runoff and saltwater intrusion under land. The model has been calibrated with the aid of measured groundwater levels and salinity distributions. Figure 8-11 gives a schematic illustration of the groundwater flow pattern on the site based on the model calculations. The study shows the following:

- The groundwater flow is directed from the highlands in the west down towards the coast. The discharge areas for a hypothetical repository at Aberg will be the sea bays that surround the island.
- Groundwater recharge gives rise to a lens of fresh water underneath the island down to a depth of around 200 m. The corresponding depth in the bordering Laxemar area is 700–800 m.
- The flow rate at repository depth on the hypothetical repository site is typically 3 litres/($m^2 \cdot y$) in the coarse resolution permitted by the large-scale model. See section 9.8 for more detailed calculations.

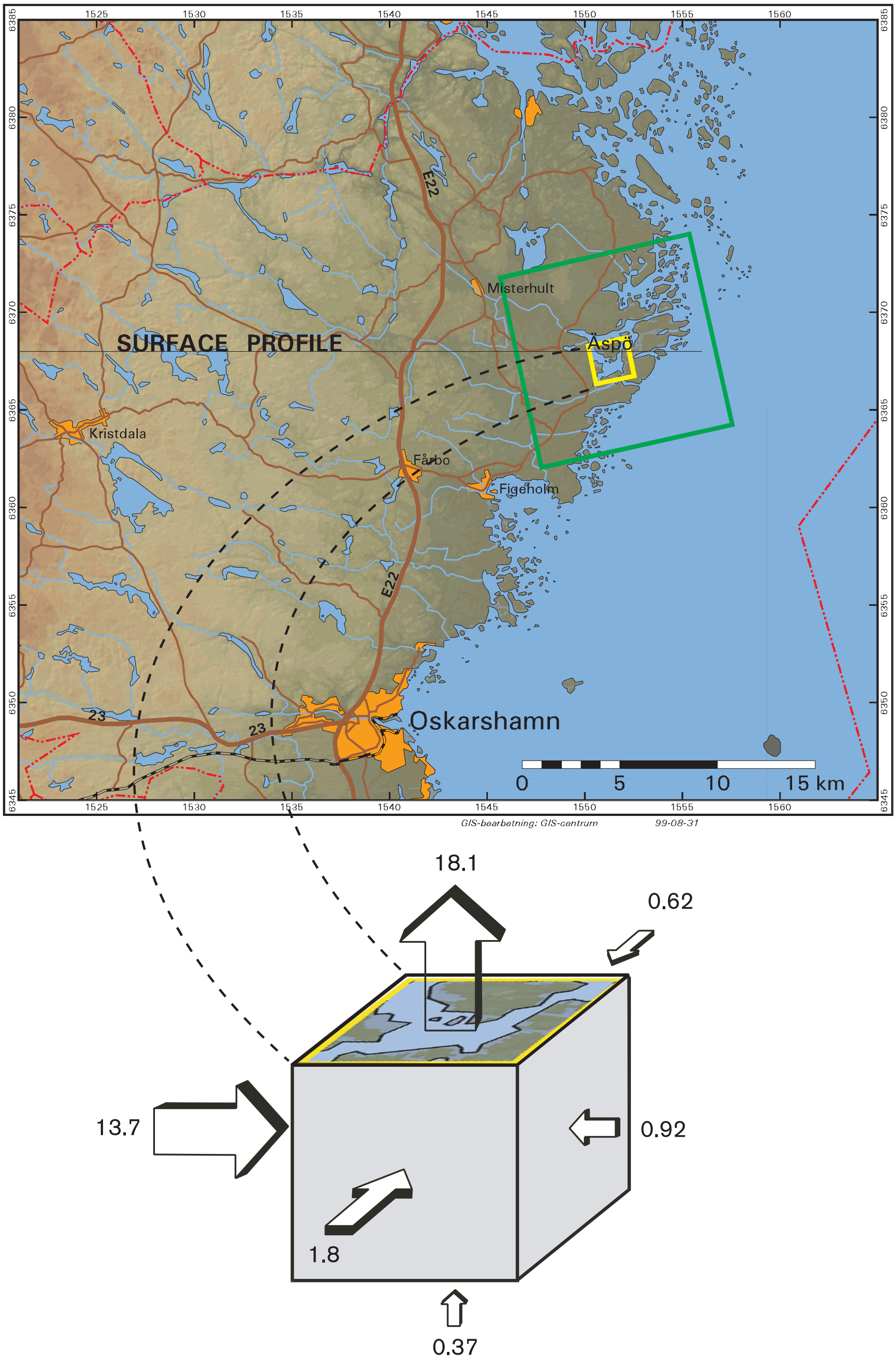

Figure 8-11. *The upper figure shows the model area for large-scale (green) and local (yellow) groundwater modelling at Aberg. The lower figure shows aggregate flows over the boundary surfaces to the local model (litres/second) as calculated by the large-scale model. The local model area is 2,400 x 2,200 x 1,250 m*^{3}.

Large-scale natural flow situation at Beberg

The site is situated about 15 km east of the northern coast of Uppland County in relatively low-lying terrain with flat outcrops, mires and small lakes (Figure 8-12). The elevation above sea level in the surrounding region varies between 0 and 60 m and the mean elevation in the region is about 30 m. The northern part of the region is drained by the Dalälven, Tämnarån, Forsmarksån and Olandsån rivers. The southern part is drained by Lake Mälaren via the Öresundaån and Fyrisån rivers. The groundwater table in the region is relatively even due to a flat topography. The regional groundwater flow is directed from southwest towards northeast /Andersson et al, 1991/.

A 150 km^2 large area is studied in a large-scale flow model for Beberg /Hartley et al, 1998/. To understand the groundwater flow and salinity distribution at Beberg, it is necessary to take into account the area's historic evolution over the last few millennia. In the study it is assumed that during the period from 9,000 to 4,000 years ago, when the Yoldia and Litorina seas covered the site, the rock was completely saturated with saline groundwater. The model simulates the evolution during the period from Litorina to the present. Figure 8-12 shows a schematic illustration of the groundwater flow pattern on the site. The study shows the following:

- The area has two possible discharge pathways: East of the hypothetical repository there is a relatively short flow path that follows a vertical fracture zone; to the west there is a longer conductor zone through the rock mass.
- The high permeability contrast between rock mass (rock domain) and fracture zones (conductor domain) makes the fracture zones the dominant flow paths.
- The density variations caused by varying salinities have a great influence on the groundwater flow. The saline groundwater strives downward so that the length of the flow paths and the groundwater's travel time are prolonged.
- The ongoing large-scale evolution since the most recent ice age is also a major influence on the groundwater flow at Beberg, which changes over time for this reason.
- The groundwater flux at repository depth on the hypothetical repository site is typically 1 litre/($m^2 \cdot y$) in the coarse resolution permitted by the large-scale model. See section 9.8 for more detailed calculations.

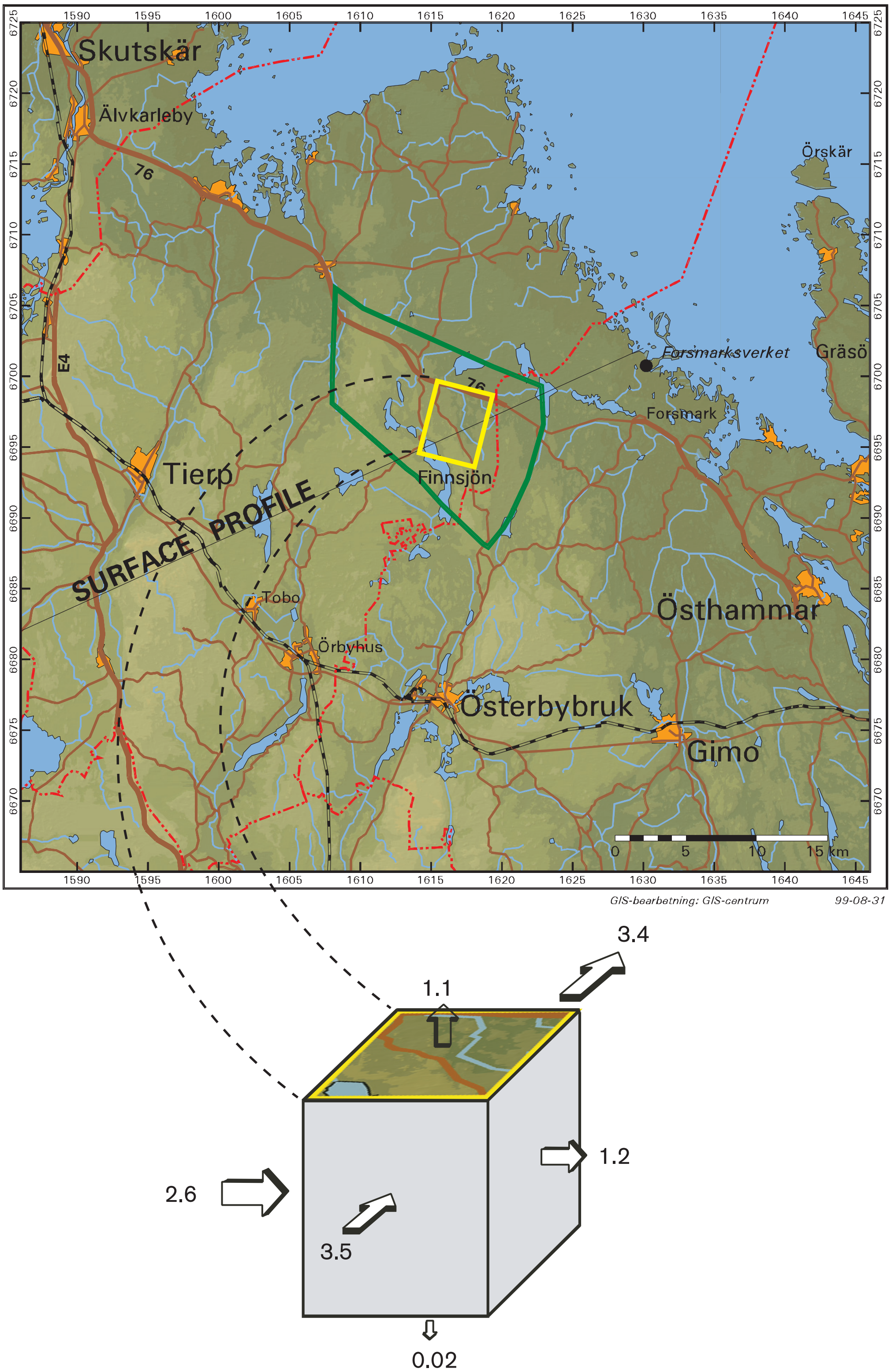

Figure 8-12. The upper figure shows the model area for large-scale (green) and local (yellow) groundwater modelling at Beberg. The lower figure shows aggregate flows over the boundary surfaces to the local model (litres/second) as calculated by the large-scale model. The local model area is 4,130 x 5,355 x 1,505 m^3.

Large-scale natural flow situation at Ceberg

In contrast to Aberg and Beberg, the area around Ceberg has a significant topographical relief with an elevation varying between about 0 and 300 metres above sea level. The area lies between the Husån and Gideälven rivers and has a relatively even topography. Both the geographic location of wells and the contours of the groundwater map indicate that the groundwater system on the central plateau in the region is dominated by a recharge area and that discharge takes place to streams in the fracture valleys /Walker et al, 1997/. It is reasonable to assume that the regional groundwater system is driven by the topography and runs from the highlands in the north and west through the study site towards the sea.

In the large-scale flow model for Ceberg /Boghammar et al, 1997/, a 300 km^2 large area is studied. No saline groundwater has been encountered in boreholes down to 700 m depth on the site, and rough calculations confirm that saline groundwater should only be encountered at greater depths. Density-driven groundwater flow has therefore been neglected in the large-scale calculations. Figure 8-13 shows a schematic illustration of the groundwater flow pattern on the site. The study shows the following:

- The water that passes through the study site at 500 m depth discharges mainly in three different areas east, south and west of the repository site.
- The groundwater flow is controlled mainly by local factors. Large-scale groundwater movements can only be seen much deeper than typical repository depth, and these movements are furthermore very slow.
- The flow at repository depth on the hypothetical repository site is typically 0.03 litres/($m^2 \cdot y$) in the coarse resolution permitted by the large-scale model. See section 9.8 for more detailed calculations.

Comparisons between Aberg, Beberg and Ceberg

The study methodology used for the three sites differs quite a bit. A comparison of the above descriptions nonetheless yields the following:

- Differences in the hydrogeological character of the sites are dependent on general hydrological features such as recharge and discharge areas, topographical relief and proportions of saline and non-saline water.
- The interpreted hydraulic conductivity in Aberg and Beberg lies on the same level, while Ceberg has lower conductivity. This also determines to a high degree the calculated flows at typical repository depth.
- The contrast in hydraulic conductivity between fracture zones and rock mass is lower in Ceberg than at other sites.
- The calculated natural gradients at repository depth for the three sites are 0.05–0.2 percent for Aberg, 0.2–0.3 percent for Beberg and 0.5–0.6 percent for Ceberg /Svensson, 1997; Hartley et al, 1998; Boghammar et al, 1997/.

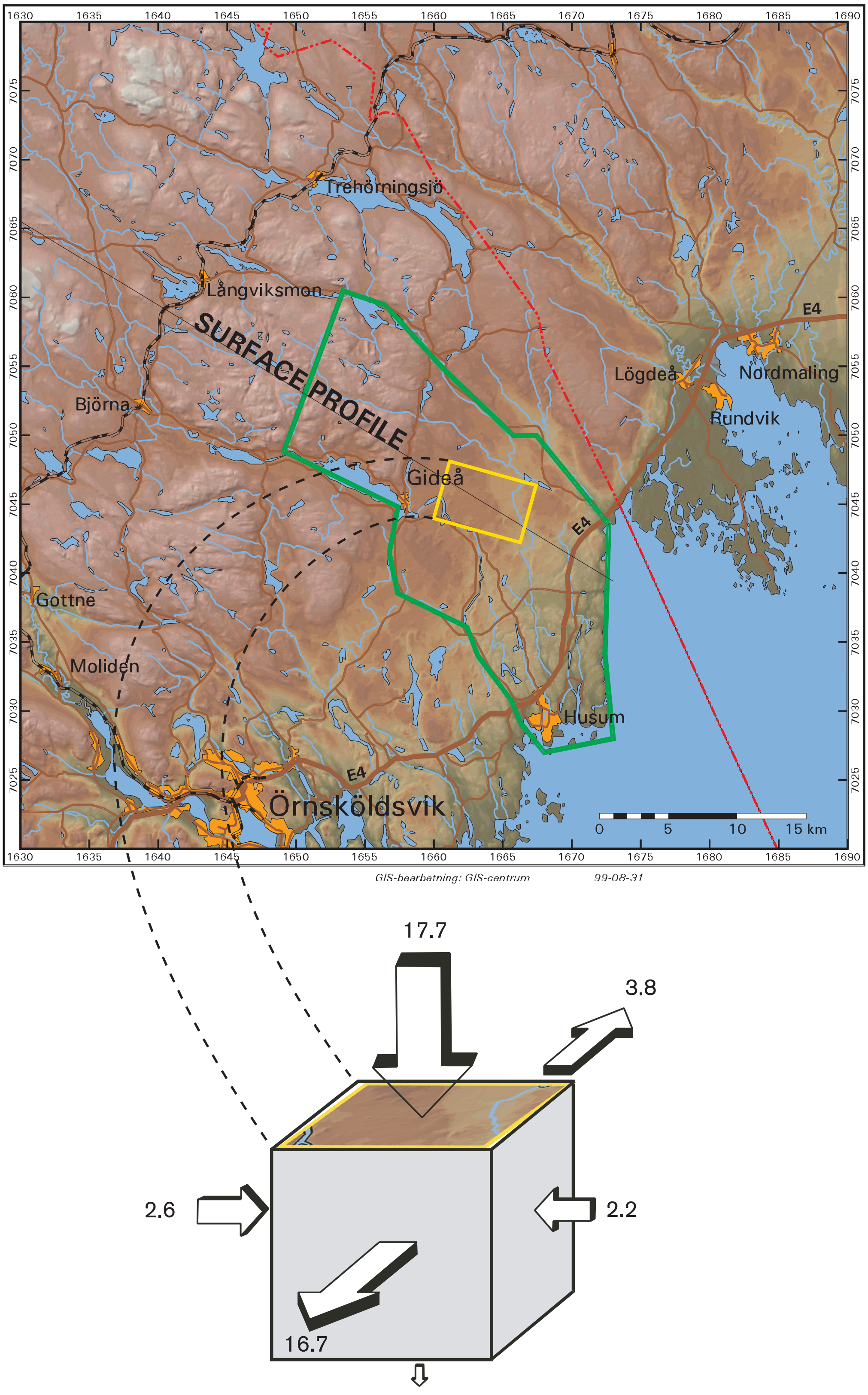

***Figure 8-13.** The upper figure shows the model area for large-scale (green) and local (yellow) groundwater modelling at Ceberg. The lower figure shows aggregate flows over the boundary surfaces to the local model (litres/second) as calculated by the large-scale model. The local model area is 6,510 x 4,290 x 1,190 m³.*

Long-term changes in the flow situations

Land uplift leads to changes in the long-term natural flow pattern. Salinities (densities) also vary in the long term, which can affect flow.

Voss and Andersson /1993/ note that shoreline displacement, i.e. the combined effect of postglacial land uplift and sea level lowering, is an important hydrological process for areas in the Baltic Shield.

Today's shoreline displacement is particularly important to describe during the current climatic period extending approximately 5,000 years into the future. After this time, in other words for most of the lifetime of the repository, other conditions are expected to dominate. These conditions are described in greater detail in Chapter 10 on the climate scenario.

Shoreline displacement has not been taken into account in the regional modelling studies of Aberg and Ceberg. At Beberg, the transient historic evolution has been taken into account as described above; however, simulation of the future has not been done.

In a supplementary study for Aberg /Svensson, 1999/, the historic evolution is simulated from 10,000 years before present to 5,000 years after present. The same geological-structural model and hydrogeological properties are used as in Svensson /1997/. The transient model /Svensson, 1999/ can qualitatively explain the chemical composition of the groundwater, i.e. how different water types have dominated the groundwater at Aberg during different periods. The model also predicts slightly increasing specific flows at repository level and slightly shorter water travel times from repository level to biosphere 5,000 years in the future compared with the present-day situation. These differences are, however, small compared with other uncertainties.

In a similar manner, Hartley et al /1998/ note that the effect of land uplift is negligible in the calculation of water travel times and exit points to the biosphere for present-day conditions at Beberg. This is due to the fact that the coast receded several kilometres from Beberg more than 2,000 years ago. Harley et al /1998/ contend that land uplift is a more important process for other sites closer to the present-day coastline.

8.7.3 Hydromechanical evolution in buffer/backfill

When the repository has been closed, the buffer will absorb water from the surrounding rock. The saturated buffer will develop a swelling pressure that acts on the rock, canister and backfill mechanically. Water transport in the unsaturated buffer is a complex process which is dependent on factors such as temperature and smectite and water content in the different parts of the buffer. The most important driving force for water saturation is a negative capillary pressure (suction) in the pores in the buffer which leads to water uptake from the rock.

It is not essential to describe the details of the water saturation process in the safety assessment. It is nonetheless important to have a picture of how water saturation takes place, since the state of the buffer following the process is the starting point for the continued description of repository performance.

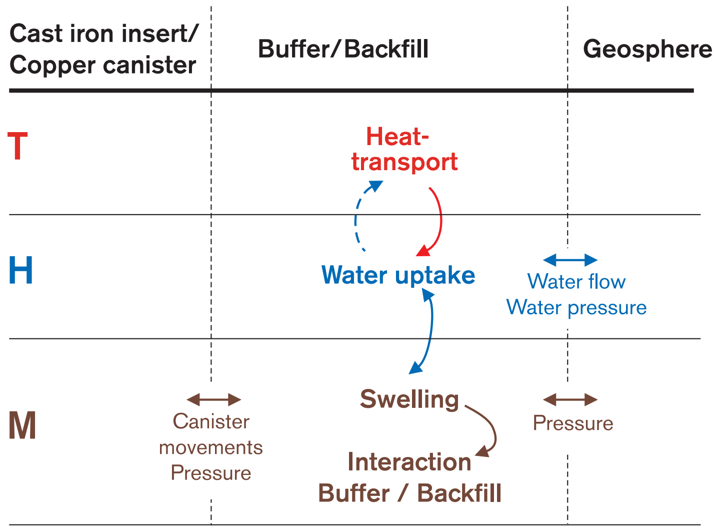

Figure 8-14. The processes included in the modelling of the hydromechanical evolution of the buffer.

The water saturation process is coupled to the thermal evolution of the buffer, since the temperature distribution in the buffer plays a decisive role in the saturation process. Via swelling there is also a strong coupling to the mechanical evolution. Both canister and backfill material in the tunnel above the deposition hole are affected mechanically by swelling. The hydraulic interaction between buffer and rock is of crucial importance for saturation. The hydraulic conditions in the rock nearest the deposition hole determine how the saturation process proceeds in time.

All of these processes and couplings have been studied in an integrated modelling where the focus is on the hydraulic evolution of the buffer /Börgesson and Hernelind, 1999/. Figure 8-14 shows the processes that have been included in the modelling.

The temperature distribution in the buffer is calculated for the water saturation that prevails at deposition and is then used in the hydromechanical calculations throughout the water saturation process. This simplification overestimates the temperature gradient over long periods of time, but this is of little importance for the saturation process compared with the differences in the properties of the rock in the different calculation cases.

The hydraulic evolution was then calculated for a number of different hydraulic conditions in the near-field rock. Furthermore, the swelling pressure that arises towards the end of the process was calculated for all cases. The swelling causes the buffer to expand upwards and partially displace the backfill material in the tunnel above the deposition hole. This was also modelled.

Conditions in the rock nearest the deposition hole are thus decisive for the course of the process. If the supply of water is unlimited, full water saturation is attained within a few years. A number of conditions in the rock are of importance for the water supply:

- The rock's hydraulic conductivity.
- The hydraulic conductivity of the excavation-disturbed zone around the deposition hole.

- The transmissivity of the fractures that intersect the deposition hole.
- The hydraulic conductivity of the backfill.
- The vapour pressure in the rock.
- Vaporization in the rock[1].

All of these conditions were varied in the calculations.

Typical case for water saturation

A typical case for the water saturation process is first modelled as a point of departure for discussing the importance of different conditions in the rock. The case is selected to simulate the conditions that can typically be expected around a deposition hole.

The rock matrix has a hydraulic conductivity of 10^{-13} m/s, and there is no boring-disturbed zone around the deposition hole. Two fractures intersect the hole, one in the middle of the canister and one at the bottom of the hole, and these would give a water flow of 0.01 l/min to an empty hole. The water pressure in the rock is 5 MPa and vaporization in the rock is included. The buffer is originally water-saturated to 80 percent. Table 8-4 summarizes the premises for the calculation.

Figure 8-15 shows the degree of saturation at different times. Water is absorbed from the rock matrix, but the principal transport pathways are through the fractures and the backfill. The time to reach full saturation of the entire buffer was calculated to be 12 years for this typical case.

Figure 8-16 shows the pore water pressure in the rock; tensile stresses in the water phase give negative values. If the tensile stresses exceed 1 MPa (i.e. if the pressure in the figure is less than –1 MPa), water vaporizes and the rock is drained. This is the case up to 50 cm out from the deposition hole between the fractures in the figure.

Table 8-4. Premises for calculations of the normal case for the water saturation process in the buffer.

Vaporization in rock	Yes
Boring-disturbed zone	No
Number of fractures through deposition hole	2
Hydraulic conductivity of rock matrix	10^{-13} m/s
Transmissivity of fractures	$5 \cdot 10^{-11}$ m^2s
Hydraulic conductivity of backfill	$2 \cdot 10^{-10}$ m/s
Water pressure in rock	5 MPa

[1] The unsaturated buffer has a high suction capacity. If the conductivity of the rock is low, the buffer can "suck" water out of the rock and cause tensile stresses in the water phase. If the tensile stresses exceed 1 MPa, the rock may become unsaturated, i.e. the liquid water vaporizes. The vapour phase reduces the rock's hydraulic conductivity. The importance of this has been studied in the modelling of the water saturation process by both allowing and not allowing vaporization in the rock. In cases where vaporization is not allowed, the tensile stresses can become unrealistically large and the hydraulic conductivity unrealistically high.

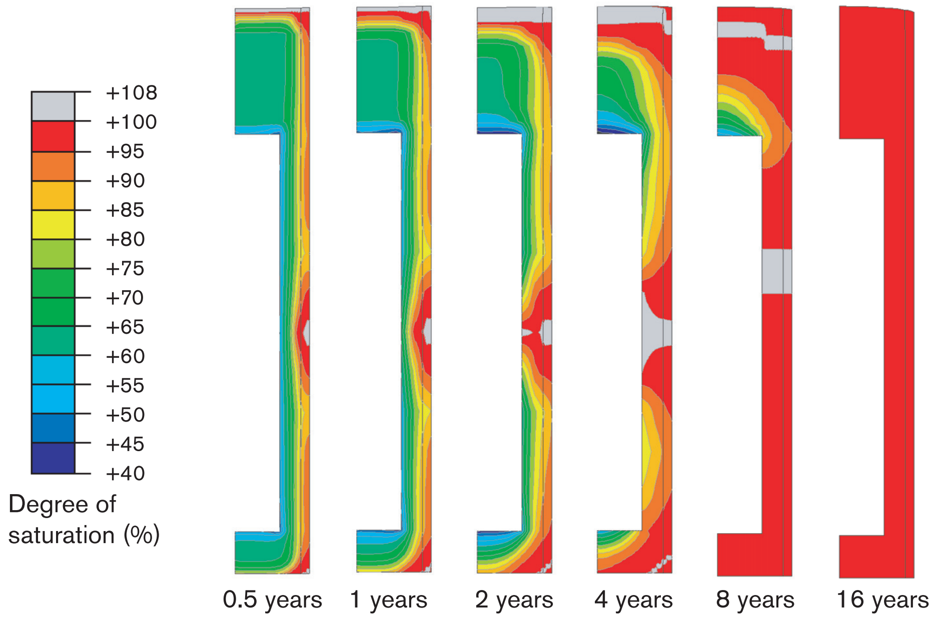

Figure 8-15. *Degree of saturation in the buffer at different times.*

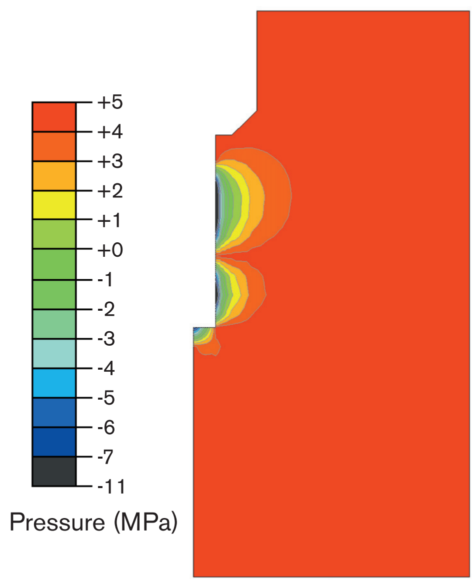

Figure 8-16. *Pore water pressure in the rock after four years. The rock is drained at the grey, blue and dark-green areas.*

Figure 8-17 shows the total pressure (sum of swelling pressure and water pressure) in the buffer as a function of time.

The following can be observed:

- The total pressure increases rapidly in the entire buffer and is a couple of MPa after only one year.
- Further pressure increase occurs as a consequence of the water saturation process and the pressure increases much faster at the fracture openings. After four years, the pressure directly opposite the fracture is about three times higher than towards its top and bottom.
- The pressure then increases faster in the lower part than at the top, partly because the buffer can expand upward to some extent, and partly because more water is supplied from below. After eight years the pressure at the bottom is three times higher than at the top, but then equalizes in ten years or so.

The material model used in the calculations of the swelling pressure gives a swelling pressure for the buffer of 8.1 MPa at constant volume. In the saturation calculation, the final swelling pressure varies locally between 7.5 and 8.75 MPa, depending on local variations in density.

The results of the calculations are of interest in a discussion of what mechanical stresses the canister will be exposed to, section 8.8.2. The load cases for which the canister has been designed entail greater stresses than those described above, especially as regards shear forces from the sides as a consequence of uneven swelling. An increase of the transmissivity in the fractures does not affect the unevenness in the pressure build-up, since at $5 \cdot 10^{-11}$ m^2s (the case above) the fracture already supplies so much water that the properties of the buffer control the saturation rate.

As a result of the swelling, the canister moves upward at the same time as the buffer partially displaces the backfill material above the deposition hole. These movements are counteracted by the swelling pressure and weight of the backfill in a manner determined by the deformability of the backfill /Process Report/. Figure 8-18 shows the movement of the canister in the deposition hole and the top of the buffer into the backfill as a function of time /Börgesson and Hernelind, 1999/.

The canister moves upward approximately one centimetre and returns to its original position after approximately 10 years. The buffer penetrates permanently about 8 centimetres into the backfill.

Variations of water saturation process

Conductivity of rock: An increase in the conductivity of the rock matrix to 10^{-10} m/s leads to nearly twice as fast saturation as in the main case, even if no fractures intersect the deposition hole. Conversely, a reduction to 10^{-14} m/s in both rock matrix and backfill leads to a very slow saturation process. After 32 years, most of the buffer is then only saturated to at most 85 percent and the rock is unsaturated several metres out from the deposition hole. The calculation was stopped after 32 years, but it presumably takes a very long time to saturate the buffer under these conditions. The situation is unreasonable, however, since the buffer is saturated through the backfill if the rock around the deposition hole is impermeable.

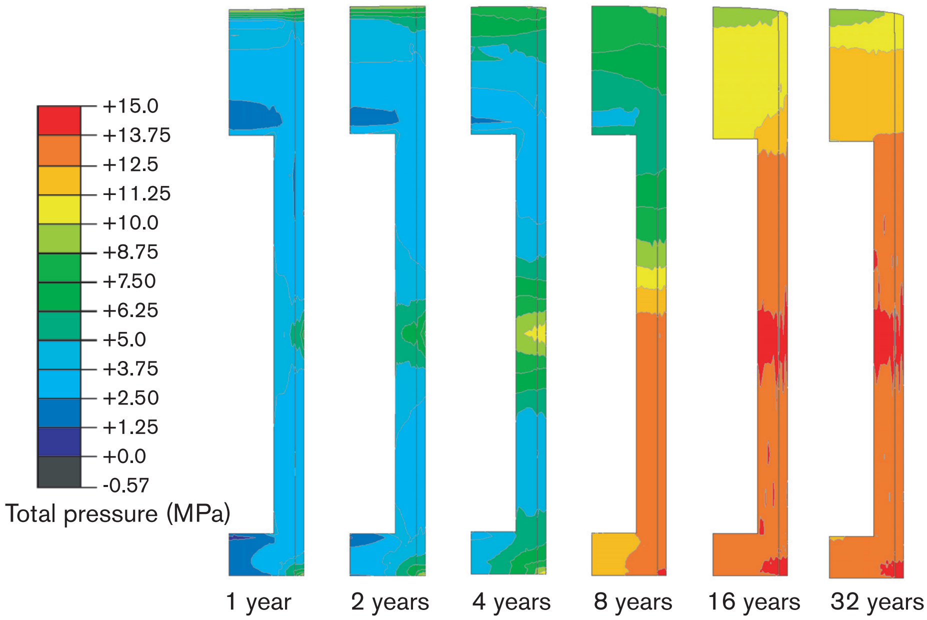

Figure 8-17. *Total pressure in the buffer at different times.*

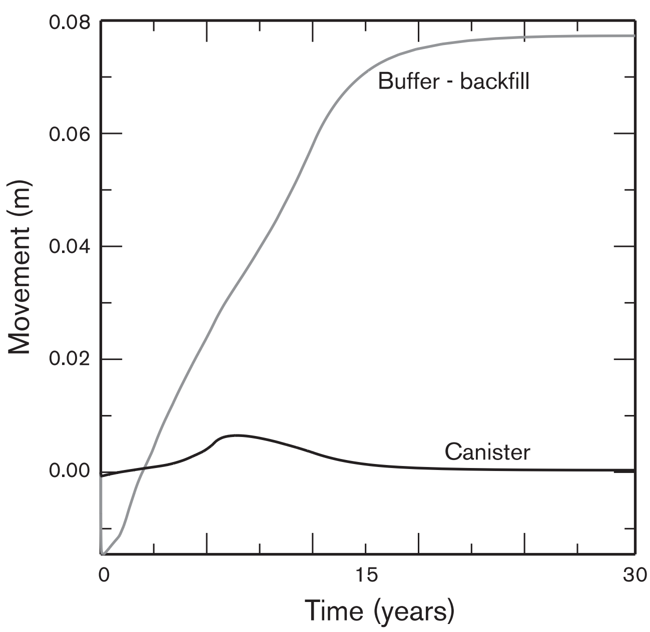

Figure 8-18. *Movement of canister and boundary between buffer and backfill as a function of time.*

External water pressure: The water saturation time has been calculated with and without external water pressure, i.e. with the pressure boundary conditions 5 and 0 MPa. The pressure is only of importance when the degree of saturation has exceeded about 95 percent, due to the fact that the bentonite's suction capacity declines sharply with increasing degree of saturation. The absence of external pressure doubles the time to attain full saturation.

Disturbed zone: In this context, the disturbed zone is a boring-disturbed zone about 1 cm wide at the periphery of the deposition hole. According to the calculations, such a zone is of limited importance for the saturation process because:

- If fractures intersect the deposition hole, they will dominate the water supply rate.
- If there are fractures, the disturbed zone facilitates the supply of water to the buffer, but their transport capacity is limited and the negative pressure in the rock is almost as great as when there is no zone.

The conclusion is that the presence of a boring-disturbed zone increases the water saturation rate by 20 percent at most.

Presence of fractures: The water saturation time has been calculated with and without two water-bearing fractures that intersect the wall of the deposition hole. In the (unrealistic) cases where water vaporization in the rock is not included, the saturation time decreases by approximately 15 percent if the fractures are present. With vaporization the effect is greater, the saturation time decreases by approximately 30 percent. This is because the unsaturated rock has a lower conductivity and the importance of the fractures is then greater.

Transmissivity of the fractures: The transmissivity of the two fractures that intersect the deposition hole was varied between $5 \cdot 10^{-12}$ and $5 \cdot 10^{-10}$ $m^2 s$, which gives a total inflow to the deposition hole of between 0.01 and 1 litre/minute. The results of these cases are identical, which means that fractures with low conductivity also supply enough water for the "needs" of the buffer.

Vaporization in the rock: The effect of water vaporization has been studied in several different cases. The conclusion is that vaporization is of great importance for the water saturation process if the rock matrix is the dominant transport pathway for water, but is of limited importance if there are other transport pathways.

Properties of buffer after saturation

When full water saturation has been reached, the buffer has the hydraulic and mechanical properties that are crucial to its long-term function in the repository. Its hydraulic conductivity is less than 10^{-12} m/s, which means that diffusion is the dominant transport mechanism between canister and rock. The swelling pressure has built up to over 5 MPa, which means that the canister is held in place and that the buffer can "self-heal" any damages.

8.7.4 Confidence

Process understanding, buffer/backfill

Buffer/backfill: The understanding of the processes that drive water transport in unsaturated buffer and backfill material and the knowledge of how the processes are influenced by various factors is good enough to carry out reliable model calculations in the safety assessment /Process Report/.

Confidence in models and data for buffer/backfill

The calculations require hydraulic and mechanical data on buffer/backfill and data on the hydraulic conditions in the rock around deposition holes, which constitutes the predominant uncertainty in the description of the hydraulic evolution of the repository.

The quality of input data and models used in the calculations is judged to be sufficient to carry out an adequate analysis of the hydraulic evolution in the base scenario. Precision in the calculations would increase with better knowledge of the hydraulic properties around individual deposition holes, which cannot be expected until the repository has been built. Long-term hydromechanical consequences of chemical changes in the buffer and backfill materials are discussed in section 8.9.3.

Confidence, geosphere

Our process understanding is good and the quality of models and data for the hydraulic evolution in the base scenario are deemed sufficient. The structure and hydraulic properties of the fracture system constitute a fundamental uncertainty in the geosphere as well. An exhaustive discussion can be found in Chapter 9 on the canister defect scenario.

8.7.5 Conclusions

The calculations presented above show that the time required to achieve full water saturation lies between 6 and 35 years for all variations, except the one where the rock mass has extremely low conductivity. This difference is of no practical importance for the performance of the repository. In the case with extremely low conductivity, the buffer is expected to be saturated by water inflow from the backfill, but this process has not been modelled.

When full water saturation has been reached, the buffer has the hydraulic and mechanical properties that are crucial to its long-term performance in the repository. Its hydraulic conductivity is less than 10^{-12} m/s, which means that diffusion is the dominant transport mechanism between canister and rock. The swelling pressure has built up to approximately 8 MPa, which means that the buffer can “self-heal” any damages.

The differences in the hydraulic conductivity of the rock mass at Aberg, Beberg and Ceberg influence the water saturation time. It is likely that differences in hydraulic properties between different deposition holes on the same site are greater than the differences between the sites, since all sites are expected to have some deposition holes in very impervious rock without water-bearing fractures.

Confidence in understanding, models and data is deemed to be sufficient for the base scenario.

For conclusions concerning the hydraulic evolution of the geosphere, see Chapter 9.

8.8 Mechanical evolution

8.8.1 Overview

The fuel is mechanically isolated from its surroundings as long as the canister retains its mechanical stability.

After deposition, the mechanical evolution will be dominated in the short term by the fact that the buffer swells due to water uptake and exerts a growing swelling pressure against canister, backfill and deposition hole walls. In the long term, mechanical processes in the geosphere play a decisive role in the mechanical evolution of the repository.

Ultimately, it is the mechanical strength of the cast iron insert that determines the consequences of the repository's mechanical evolution.

Mechanical processes

The following is a summary from the Process Report of the descriptions of the mechanical processes that have a bearing on the base scenario.

A mechanical state prevails in the **geosphere** where the state of stress in the host rock which prevailed before repository construction has been altered due to stress transformations around the repository's cavities. Stress transformations lead to local deformations of the fracture system. Locally, fractures can also be affected mechanically by the construction process.

The further mechanical evolution is determined by how the geosphere responds to the different loads to which it is subjected. The loads may consist of the thermal expansion to which the heating of the repository leads, the pressure from swelling buffer/backfill, and large-scale tectonic changes. The geosphere's reaction to the loadings is given by the stress-deformation relationships that exist in the system. The changes/deformations can occur in the form of fracturing, reactivation (movements in existing fractures) or rock creep (slow redistributions in the rock). Movements in intact rock, i.e. compression/expansion of otherwise intact rock blocks, also occur. An integrated description of the mechanical long-term evolution in the geosphere is given in section 8.8.3.

In **buffer and backfill**, the water uptake after deposition will lead to swelling. In the buffer, the heating moreover leads to thermal expansion of the pore water. The buffer with its higher clay content will swell more than the backfill, causing a mechanical interaction between buffer and backfill whereby the buffer is expected to push up into the backfilled tunnel. Buffer movements can also lead to canister movements, so that the canister could move in the deposition hole. All of these processes are dealt with in section 8.7.3 above. The swelling also leads to clay intrusion in the fractures of the rock. In the long term, chemical changes in the buffer can also lead to modification of its swelling properties, see section 8.9.3 under chemical evolution.

An important question in the mechanical evolution of the repository is whether the **canister**, where the cast iron insert constitutes an important mechanical barrier, will withstand the mechanical stresses to which it may be subjected under various conditions. In the process description the evolution is expressed by the processes deformation of cast iron insert and deformation of copper canister. As long as the copper canister is intact, the deformations that can occur are caused by external loads from above all the buffer's swelling pressure and the pore water pressure. The mechanical evolution of the canister is described more fully in section 8.8.2.

As long as the cast iron insert and copper canister are intact, mechanical stresses between fuel and canister arise only as a result of the pressure that is built up in the canister's cavity due to helium formation caused by α decay in the fuel. The effect of internal pressure build-up on the canister is negligible, see further the Process Report.

In the mechanically isolated **fuel**, failure of the Zircaloy cladding can occur, due among other things to increased gas pressure caused by post-closure temperature increases in the fuel. The process is promoted by chemical changes that can occur during the operating period, e.g. hydride formation and embrittlement, see further the Process Report. The process has no bearing on long-term safety as long as the copper canister is intact and is therefore not dealt with further in the base scenario.

Couplings to other aspects of repository evolution

Heating of the repository leads to thermal expansion in all parts of the repository, which comprises part of the mechanical evolution of the repository. The buffer's water uptake leads to swelling, which affects canister and geosphere mechanically.

Furthermore, the mechanical processes lead to geometric changes, albeit these are usually small. The geometric shape of each part of the repository influences more or less all processes in the repository system. Fracture geometry, for example, is of crucial importance for groundwater flow.

What needs to be shown in the base scenario?

A more detailed description of the following aspects of the mechanical evolution of the repository is given in coming sections:

- The mechanical evolution of the canister, given the evolution that is expected in buffer/backfill. The effects of rock movements on the canister are also analyzed.
- A description of the geosphere's mechanical evolution and its long-term stability.

The description of the mechanical evolution of buffer/backfill has been integrated with the description of the hydraulic evolution of these subsystems, section 8.7.3.

Importance for safety

The mechanical evolution may have a direct bearing on safety, since the mechanical stresses on the canister could affect its isolating capacity.

8.8.2 Mechanical evolution of the canister

The material in this section is a summary of the description of the mechanical processes for cast iron insert/copper canister in the Process Report.

The canister's cast iron insert is the most important mechanical barrier in the repository system. An important part of the safety assessment is therefore to show how the canister reacts over time to the mechanical stresses it may be subjected to by buffer and rock. Via the buffer, the canister is subjected to swelling pressure and the water pressure at repository depth. Mechanical stresses on the canister can also be caused by movements in the rock.

Small loads cause elastic deformation of the canister, which means it will resume its original shape if the load is removed. Larger loads may lead to permanent or plastic deformation. It is common, but not necessary, to design structures with an ample safety margin to the borderline between elastic and plastic deformation. This yield strength or yield stress is therefore of importance in studies of canister strength. The yield stress of the material in the cast iron insert is approximately 235 MPa, while that of the material in the copper canister is around 45 MPa.

The strength of the canister insert has been calculated /Ekberg, 1995/ for an external, evenly distributed pressure. The inner supports in the insert enable it to retain its shape even if local deformations arise. The collapse pressures have therefore been assumed to lie at a pressure level that gives a strain equivalent to 80 percent of the rupture strain. With this assumption, the insert in the BWR version will withstand pressures of 80 MPa, while the one in the PWR version will withstand 110 MPa. This is far above the external pressure of 12 MPa composed of 7 MPa swelling pressure from the bentonite and 5 MPa water pressure at 500 metres depth to which the canister is subjected in the deep repository.

To enable the insert to be inserted in the copper canister, it has an outside diameter that is 3.5 mm less than the inside diameter of the copper canister. With this clearance, a maximum strain in the copper wall of less than 4 percent is guaranteed when the copper canister is pressed against the insert as the water pressure and the bentonite's swelling pressure build up. The creep strain can be estimated at 10 percent. The maximum strain occurs locally on the inside of the shell near the transition to the lid.

Uneven swelling pressure

During the water saturation phase, the pressure may be unevenly distributed over the canister due to the hydraulic evolution in the buffer, see section 8.7.3. After saturation, permanent minor pressure disequilibria may occur if the canister is tilted in the deposition hole or if the walls of the hole are uneven. The time required to saturate the buffer is dependent on the supply of water and varies between a couple of years and several tens of years.

Strength calculations have been carried out for a number of load cases to analyze the mechanical consequences for the canister in such situations /Werme, 1998; Börgesson and Hernelind, 1998/. The cases are designed to be pessimistic simplifications of not entirely unreasonable situations.

Water saturation phase: Bounding calculations for conceivable situations during the water saturation phase have been carried out for three cases. In all cases, pressure differences, and above all degree of restraint, have been exaggerated compared with expected conditions in the deep repository. The load cases give greater stresses than the cases for the hydraulic evolution in the buffer described in section 8.7.3.

Case 1. The canister is rigidly fixed on both end surfaces and along one-tenth of the length of the cylindrical surface nearest the ends. An evenly distributed horizontal load corresponding to fully developed bentonite swelling pressure (7 MPa) acts along one side of the remaining canister surface.

Case 2. The canister is supported by a contact one-tenth of the length of the cylindrical surface from the ends. An evenly distributed horizontal load corresponding to fully developed bentonite swelling pressure (7 MPa) acts along one side of the remaining canister surface.

Case 3. The canister is rigidly fixed on one end surface and 1 m along the cylindrical surface nearest this end surface. An evenly distributed horizontal load corresponding to fully developed bentonite swelling pressure (7 MPa) acts along one side of the remaining canister surface.

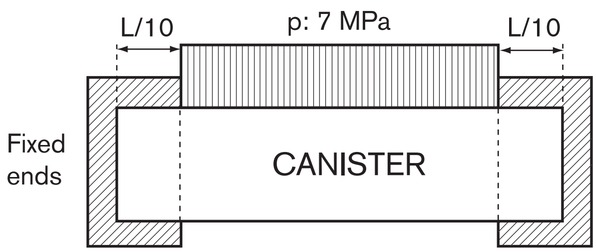

Figure 8-19. *Load case 1.*

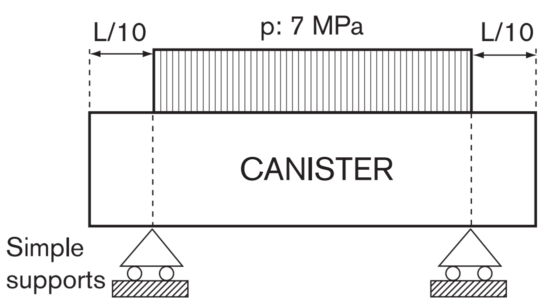

Figure 8-20. *Load case 2.*

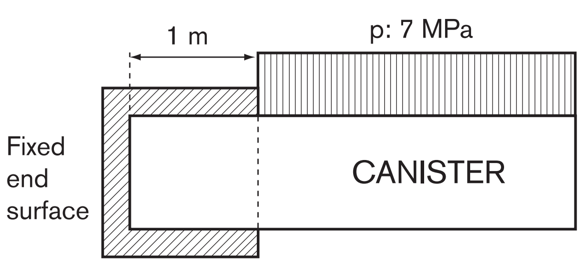

Figure 8-21. *Load case 3.*

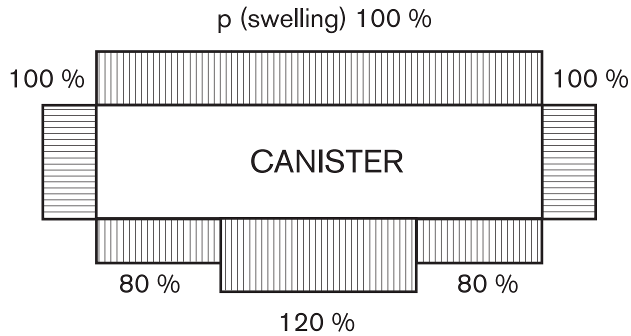

Figure 8-22. *Load case 4.*

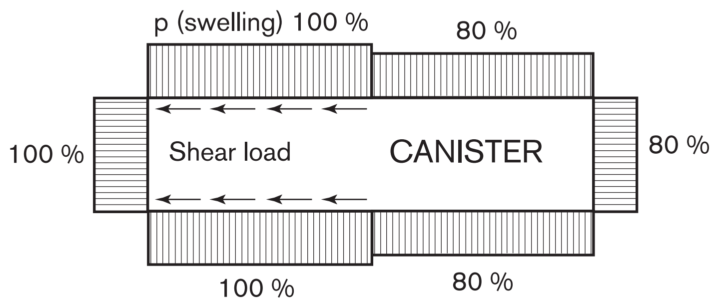

Figure 8-23. *Load case 5.*

After water saturation: Two cases have been calculated for conceivable situations after water saturation.

Case 4. The swelling pressure is fully developed on one side of the canister's cylindrical surface and on the end surfaces. On the other side of the cylindrical surface, the swelling pressure is 20 percent elevated along the central half and 20 percent reduced along the remaining quarters at the ends of the canister.

Case 5. The swelling pressure is fully developed around the bottom half of the canister, while the swelling pressure is 20 percent lower around the top half. The resulting upward force, which results from the differences in pressure against the canister's end surfaces, is balanced by a shear force along the bottom half of the cylindrical surface. This load case thus gives a load on the copper shell.

If the mechanical stresses in the canister exceed the yield strength, the canister will be permanently deformed. For cases 1, 2 and 4, simple handbook calculations are sufficient to conclude that the maximum bending stress lies below the canister insert's yield strength, which is 235 MPa at 100ºC, see Table 8-5.

Tabell 8-5. Bending moment and bending stress for load cases 1, 2 and 4 according to handbook calculations.

Load case	Maximum bending moment (MNm)	Maximum bending stress (MPa)
1	7.2	122
2	10.8	183
4	1.7	29

For case 3, handbook calculations are far too crude a method for determining the strength of the insert, in part because the properties of the buffer are not included. For cases 2 and 3, finite-element calculations have therefore been performed, where the material properties of the bentonite have also been taken into account /Börgesson and Hernelind, 1998/. The maximum stresses in the canister insert were then found to be less than 55 MPa.

In load case 5, the whole load can be imagined to be borne by the copper shell. The unbalanced force between the ends of the canister must be borne by the axial friction between copper and bentonite. If the friction between shell and insert is disregarded, the force will be absorbed by the shell. The axial force in the copper shell will then be less than 10 MPa according to a handbook calculation, compared with the yield strength of 45 MPa.

No skewed loads of the postulated kinds are thus judged to be capable of leading to canister damage.

Rock movements

To be able to judge the consequences of rock movements around deposition holes, the strength of the canister has also been preliminarily calculated for a postulated displacement of 0.1 metre lasting 30 days along a horizontal fracture /Börgesson, 1992/. Rock movements are discussed in the next section and in Chapter 11, the tectonics scenario.

The investigated canister was of an earlier design with a self-supporting insert consisting of a steel tube. The collapse load for this canister design lies in the range 45–55 MPa, to be compared with 80 and 110 MPa, respectively, for the current BWR and PWR designs. The calculations can therefore be regarded as pessimistic in this respect. The results showed that rock movements on the order of 0.1 metre do not lead to immediate canister failure. The canister was deformed plastically, but the copper shell remained unbreached. The plastic strains in the copper shell were less than 2.5 percent, which is low in comparison with the 40 percent the material can withstand.

A pessimistic estimate of the creep deformation in the copper canister after the rock movement showed that the deformation during a period of up to 100,000 years could lead to strains of approximately 6 percent in the cylindrical part of the copper canister, and up to 36 percent in the lid. The rupture strain can be estimated at 10 percent. The possibility that a 0.1 metre rock movement could lead to canister damage after a very long time can therefore not be ruled out.

If the rock movement is faster, this is in practice equivalent to a higher bentonite density. If the shear movement takes place in one second instead of 30 days, this would be equivalent to a buffer density of approximately 2.13 g/cm^3. Calculations for this density have been done on a scale of 1/10 for a canister of solid copper. The calculations showed plastic strains of up to 4 percent. This is far from the expected rupture strain for the copper material. Since the calculations were carried out for a canister of solid copper, the size of the strains is probably also overestimated. In the same way as for the slower shear movement, however, a later creep rupture of the canister cannot be ruled out.

In the following rock-mechanical analyses in the base scenario, section 8.8.3, and in the earthquake analyses in Chapter 11, it is pessimistically assumed that rock movements of a magnitude of 0.1 metre and more around a deposition hole could lead to canister damage.

8.8.3 Mechanical evolution in the geosphere

The different processes that control the mechanical evolution of the geosphere are discussed in detail in the Process Report. The following text is based to a high degree on the text in the Process Report.

General

The canister and buffer/backfill interact mechanically with the geosphere. The buffer/backfill affects the rock mass in the vicinity of the repository, and the canister and buffer/backfill are affected by the fact that the rock mass in the host rock is subjected to loads due to heating, glaciation or large-scale movements in the earth's crust. The repository can also be affected by slow, time-dependent changes in the mechanical properties of the rock mass.

The rock mass is deformed by load changes in a way that is dependent on the rock structure and the stress-deformation relationships that apply to the components involved, i.e. the intact rock and the fractures. Load changes also influence the state of stress in the rock mass.

Minor movements in intact rock occur in connection with all load changes, but the properties of the rock mass are such that significant deformations primarily take place along existing fractures, reactivation. The term "reactivation" refers here to all types of fracture movements, not just ones that have occurred previously or are occurring now due to movements in the earth's crust, but also ones caused by local disturbances, such as tunnelling. Two types of movement occur along fractures: shear movements entailing relative displacements of the fracture surfaces, and normal movements entailing changes in fracture width. Local stress concentrations in small volumes without suitably oriented fractures can give rise to failure in intact rock, fracturing. Fracturing can take place both by formation of new fractures and propagation of existing fractures.

Shear movements that take place in the near field can have a direct bearing on safety. If the displacement sum exceeds 0.1 metre and the movement takes place along a fracture that intersects a deposition hole, the canister may be damaged, see further section 8.8.2. Since large shear movements can only take place along fractures or fracture zones of great extent in their own plane, deposition hole positions that are intersected by large fractures are avoided when the repository is built.

Shear movements that take place on a larger scale and at some distance from tunnels and deposition holes have no direct influence on safety, whether they occur due to natural causes or due to the influence of repository construction on the host rock. The influence of such movements is indirect and entails modification of the effects of different load changes, e.g. tectonic or thermal, on the state of stress in the near field. In general the effect is favourable, since the movement absorbs strain energy and limits the growth of large shear stresses in the near field.

Normal movements in fractures in the near field affect permeability around tunnels and deposition holes. The assessment for the base scenario in SR 97 is that the aggregate of the normal movements, which entails both aperture decreases and aperture increases, does not give rise to systematic permeability changes of such magnitude that they need to be quantified and taken into account in the safety assessment, see the Process Report.

Nor are larger-scale normal movements judged to give rise to such systematic effects on the permeability of the rock in the vicinity of the repository that they need to be taken into account in the safety assessment.

Fracturing, i.e. failure of intact rock, can have a direct bearing on safety if the extent of the failure is such that the geometry of the deposition hole is changed so that the pressure on the canister becomes so great or uneven that the canister is damaged. Other effects of failure, such as local changes in permeability, are judged to be of such little importance that they don't need to be quantified or taken into account in the safety assessment.

Initial state

The rock is subjected to load changes due to excavation of the rock in conjunction with repository construction. Deformations and stress redistributions take place in the zone around tunnels and deposition holes so that the tangential stresses around the cavities become large and the pressure against the cavity walls disappears. Thus, in the initial state that prevails after deposition and closure, both movements in the intact rock and movements along existing fractures have taken place. The stress concentrations in the periphery of the cavities, above all in the upper parts of the deposition holes, may be such that failure in intact rock blocks, i.e. fracturing, has also taken place. Fracturing can lead to fragmentation and minor rock breakout at the boundary of the deposition hole or in the tunnel periphery. The extent depends on the mechanical properties of the rock and the state of stress that prevailed before the repository was built (the primary state of stress).

The rock may have been directly affected or damaged by the tunnelling up to a depth of approximately one metre from the tunnel periphery. The extent of the damage depends on the tunnelling method. The mechanical properties of the rock are changed in the excavation-damaged zone. Due to the fracturing, future load changes will not give rise to as great stresses as if the rock was unaffected. Around the deposition holes, on the other hand, the damaged zone is negligible from a mechanical point of view.

At distances greater than 10–15 metres from the cavities, the rock is unaffected and the state of stress is identical to pre-mining state of stress, i.e. the primary stresses still prevail. For Swedish bedrock in general, and for the three repository sites in particular, the primary vertical stress is largely determined by the rock overburden, while the horizontal stresses are slightly greater. Variations are great, however, both between different sites and locally within smaller areas. In the case of Beberg and Ceberg, regression relationships based on rock stress measurements give a maximum horizontal stress at a depth of 500 metres of 23 MPa and 20 MPa, respectively /Ljunggren et al, 1998/. Horizontal stresses of between 35 and 40 MPa have been measured at Aberg /Leijon, 1995/. Comparisons between the states of stress at the three repository sites are, however, uncertain due to differences in measurement methods and number of measurements performed.

Water saturation of buffer and backfill

After deposition and closure, the buffer/backfill begins to be saturated with water. Even in its unsaturated condition, the highly compacted backfill provides support to the tunnel periphery. The swelling pressure that gradually develops during water saturation due to the bentonite content of the backfill is small and therefore has little effect on the state of stress in the rock. The buffer, on the other hand, will develop a swelling pressure which slightly reduces the initial tangential stresses at the deposition hole periphery. In relation to the tangential stresses that exist after boring of the deposition holes, this effect is also small. Water saturation may take ten years or so, depending on the rate at which the groundwater pressure is built up in the repository and also depending on the flow of water around the individual deposition holes, see section 8.7.3. Once the swelling pressure has developed, it will persist, provided that the physical properties of the buffer don't change.

Even if the effect of the buffer and the backfill is small in terms of stress levels, the effect when in terms of the stability of the rock nearest the cavity walls is very considerable. Cavities in heavily stressed rock usually become deformed with time by progressive failures accompanied by fragmentation and rock breakout in the most stressed portions of the periphery, i.e. parts which are in a potential failure state after rock extraction. The support of the buffer and the backfill shifts the balance from instability towards stability, thereby greatly limiting the initiation and development of such failures.

Heat pulse: Time up to 5,000 years after deposition

Immediately after deposition, at the same time the water saturation process starts, heat begins to be transferred from the canister to the rock via the buffer, see section 8.6. The heat-induced movements in the crystal matrix will to a large extent be converted into thermal stresses, since the rock cannot expand freely. At the deposition hole boundary, the temperature reaches a maximum approximately 30 years after deposition, see section 8.6.2. In the near field adjacent to the deposition holes, the thermal stresses are greatest around 50–200 years after deposition, after which they decrease partly because the temperature in the near field decreases, and partly because increasingly larger portions of the surrounding rock are heated up and expand, which reduces the constraint on the near-field rock.

The thermal stresses are great in the near field, not only because the highest temperatures occur here, but above all because the nearness to the cavity walls controls the stress state. The compression properties of buffer and backfill are such that the pressure against the cavity walls increases only marginally due to heating, while the tangential stresses in the rock around the cavities increase substantially. The state of stress with large shear stresses that prevails in the near field already in the initial state, is thus further accentuated, especially at the periphery of the deposition holes. This will result in shear movements in fractures in the near field. Calculations show that the shear movements will have a magnitude of a millimetre or so, see e.g. Shen and Stephansson /1996/. The range of the mechanical impact of the cavities is limited to approximately 10–15 metres. At greater distances from the cavities, e.g. between the deposition tunnels, the temperature increase causes the horizontal stresses to increase, while the vertical stresses are only affected marginally. The stress levels next to the deposition holes will be such that failure in intact rock can also occur. The areas that are in a failure state are small, however. Moreover, the resistance from the buffer limits both the extent of the fracturing and the consequences in the form of movement of dislodged fragments. After 5,000 years, the temperature in the area around the repository is still about 15°C higher than initially, and the thermal stresses around the cavities are 10–20 MPa, see Figure 8-24.

On the repository scale (on the order of 1,000 metres), the thermal stresses are independent of the cavities and of the deposition geometry. After approximately 50 years, a maximum increment of horizontal compressive stresses exists in a thin slice around the repository itself. Above and below this thin slice there are reductions of the initial compressive stresses. Eventually, as the heat wave propagates, the stresses are equalized in such a manner that the extent of the area with elevated horizontal stresses becomes greater, i.e. the thin slice becomes thicker, at the same time as the stress increment becomes smaller, see Figure 8-24. Outside the growing area with elevated compressive stresses there is an area with reduced horizontal compressive stresses. Just below the ground surface, this can theoretically result in horizontal tensile stresses. In reality, it can be assumed that steeply-dipping fractures and fracture zones without the capability to transmit tensile stresses are instead widened so that the horizontal stresses tend towards zero. The vertical stresses are largely determined by the rock overburden and are affected very little by the heat wave. The effect of the heat wave on the repository scale is therefore that the stress situation that prevailed initially at repository level, i.e. with stresses that are slightly greater in the horizontal direction than in the vertical direction, is reinforced, which means increased shear stresses. After a few hundred years, when the stresses have begun to equalize, the effect diminishes. However, the shear stress increment is small and gives rise to shear movements along large fracture zones that reach a maximum of a centimetre or so /Hansson et al, 1995; Israelsson, 1996/.

The repository layout, i.e. its geometric configuration, can naturally influence both the stress levels and the extent of the areas where compressive stresses are elevated or reduced due to the heat pulse. In the case of the layout that is planned for the repository in Aberg, i.e. a two-level repository with a distance of 100 metres between the two levels instead of one level, the different in relation to the single-level layout used in Beberg and Ceberg is that the slice with elevated compressive stresses is thicker and that the horizontal compressive stresses are greater /Probert and Claesson, 1997/. The difference in horizontal stress increment, and thereby in shear stress increment, is however marginal, which means that shear movements in fractures and fracture zones are of approximately the same magnitude as in the single-level repository.

The actual size of the thermal stresses, both in the near field and on the repository scale, is also dependent on the compression properties of the rock mass, both in the heated parts and in the surrounding, still-cold parts. The mechanical properties of the surrounding, unheated rock determine what volume expansion of the heated rock will be permitted and thereby contribute towards controlling the stress levels in the heated portions. The mechanical properties, e.g. the compression properties, of large rock volumes are probably influenced by scale effects, which is not usually taken into account in analyses of the thermomechanical evolution of the repository. The analyses are therefore performed with pessimistic assumptions regarding the mechanical boundary conditions. The existence of compressible fracture zones in the repository's surroundings would, for example, entail a reduction in the constraint of the heated rock, and thereby the stress levels upon heating. Figure 8-24 shows the thermal stresses in the near field and on the repository scale, calculated with the pessimistic assumption that the host rock and the surrounding rock are uniform, elastic and have material properties that correspond to small rock volumes, i.e. without regard to possible scale effects.

The effects of the thermal pulse are small from the safety viewpoint, both in terms of shear movements along fractures and fracture zones, and failure in intact rock next to the deposition holes. This has been established by numerical and analytical thermomechanical calculations performed under pessimistic assumptions regarding constraint of the repository, see the Process Report. The thermal pulse causes instability, but stability is regained by means of small deformations that are insignificant for safety.

The conclusions regarding the effects of the thermal load are based on analyses where the rock mass is assumed to have homogeneous and isotropic thermomechanical properties, while in reality there is generally a variation of rock types with different properties. The variability in rock composition differs between the three repository sites. The possible consequences of the fact that boundaries between rock types with different properties exist in areas with strongly elevated temperature, i.e. in the vicinity of the deposition holes, remains to be analyzed.

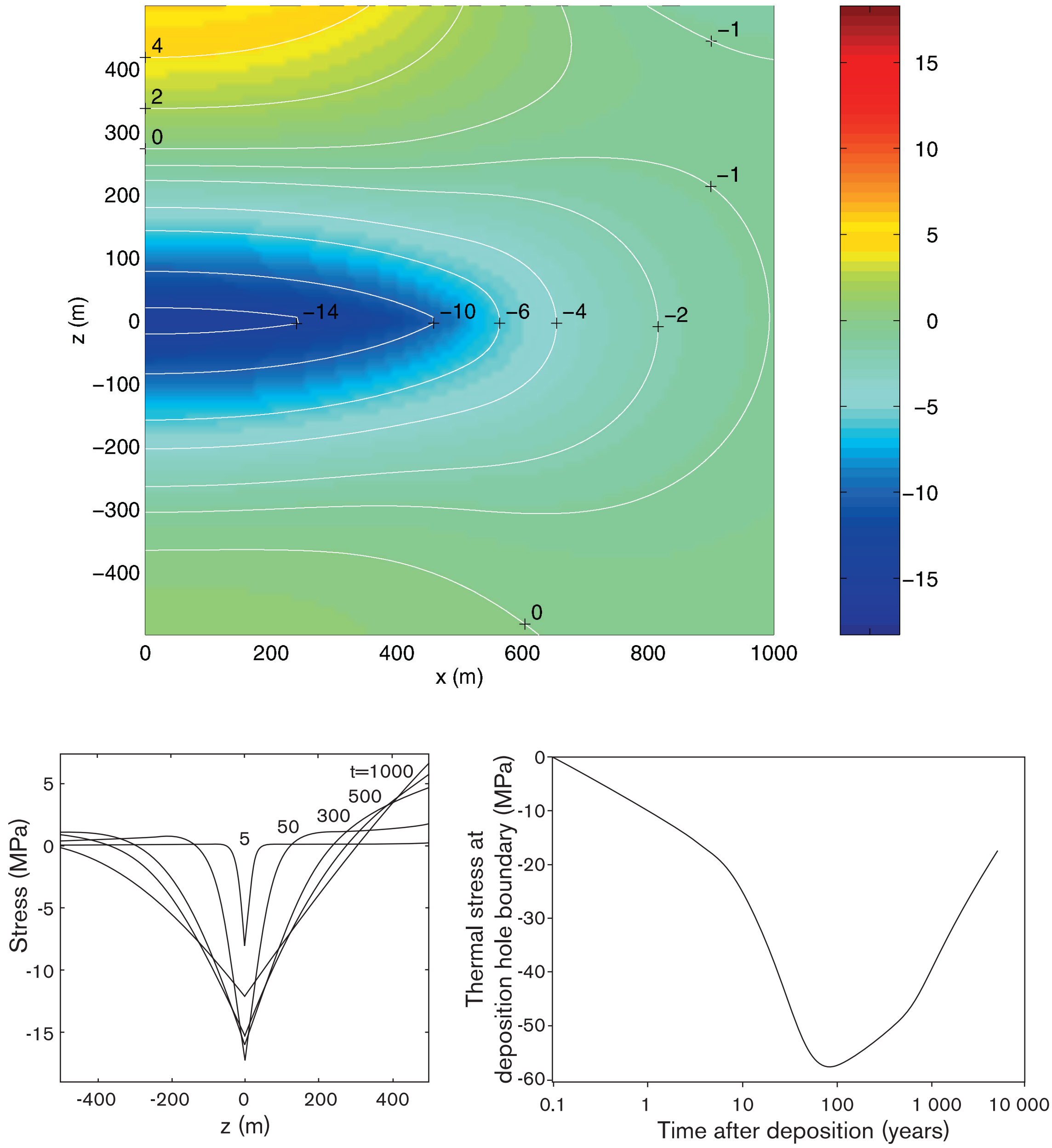

Figure 8-24. *Thermal stresses on the repository scale and in the near field. A minus sign indicates compressive stress and a plus sign tensile stress. The upper figure shows horizontal stresses after 500 years in a vertical section through the repository /from Probert and Claesson, 1997/. The lower left-hand figure shows horizontal stresses in a vertical line through the repository so that z = 500 m is at the ground surface /from Probert and Claesson, 1997/. The lower right-hand figure shows thermally generated tangential stress in a point at the periphery of a deposition hole /after Hökmark, 1996/.*

Time after heat pulse

The mechanical effects of the temperature pulse have faded away after a few thousand years. The subsequent mechanical evolution in the host rock is determined by processes with very long time horizons, which are furthermore associated with great uncertainties. For one thing, the load on the host rock can be influenced by slow largescale movements in the rock, and for another the host rock could have its own time-dependent material properties so that already acting stresses cause time-delayed deformations (creep movements).

Large-scale movements in the bedrock

The horizontal strain in the earth's crust in Sweden can be estimated at approximately 10^{-9}/year /Muir Wood, 1993/. The causes are differential land uplift, which has been going on since the most recent glaciation, as well as tectonic movements that are being transmitted to the interior of the Baltic Shield /Muir Wood, 1995/. Roughly, this corresponds to an average stress change of 5 MPa in 100,000 years, which is small compared with the uncertainty inherent in the determination of the initial natural rock stresses. The effects in the form of shear movements along fractures in the near field and failure in stressed, intact rock next to the deposition holes will be considerably smaller than corresponding effects of the thermal pulse. The uncertainties in the estimate are great, however, and are based on the assumption that the strain is evenly distributed in time and space.

It is assumed here that largescale movements in the bedrock cause time-continuous effects in the repository. Possible dynamic effects of large-scale movements are dealt with in the tectonics scenario.

Creep movements

Our knowledge of creep movements in large rock volumes over long time spans is still inadequate. The process is predicated on the presence of shear stresses, which means that the zones around tunnels and deposition holes could particularly be affected /Pusch and Hökmark, 1993/. The attempts that have been made with various rheological models to estimate the scope of and timescale for a possible creep-induced change in the geometry of the deposition holes have indicated slow processes and small deformations, despite the fact that the stabilizing influence of the buffer in the deposition hole has not been taken into account in these models. The estimates vary widely, however. Counted as radial displacement of the deposition hole boundary, values such as 10 mm in 10^9 years /Eloranta et al, 1992/ and 6 mm in 10^4 years /Pusch, 1996/ have been reported, where the latter estimate is based on pessimistic assumptions.

If the influence of the buffer is taken into account, it is possible to set bounds to the effect of a creep movement that can be hypothetically assumed to proceed as long as there are any shear stresses in the rock. Such a creep movement, which entails that the stress anisotropy around deposition holes and tunnels gradually disappears, could at most lead to compression of the buffer until its swelling pressure corresponds to the mean compressive stress in the rock, which is approximately 20 MPa for the three repository sites. This pressure is not sufficient to cause canister failure. The stress increment that could arise due to large-scale tectonic movements, i.e. 5 MPa in 100,000 years according to estimates of the average movements in the Baltic Shield, can be neglected. In reality, the mean compressive stress at repository depth is less than 20 MPa if the rock is actually deformed as described above, i.e. as a viscous fluid. The state of stress will then be hydrostatic, with a mean compressive stress equivalent to the dead weight of the rock, i.e. about 14 MPa. This type of creep movement, which entails that the rock is deformed like a viscous medium so that the arch effect around the repository cavities is lost, must, if it takes place at all, be judged to be very slow and furthermore does not cause any canister damage for the stresses that can be expected in the base scenario.

The time-delayed movements might conceivably also take place along fractures, e.g. due to successive local failures in connection with stress concentrations at irregularities in the fracture surfaces, while the rock blocks remain intact. The effect will then not be a general reduction of the diameter of the deposition holes with subsequent increase in buffer density and increased pressure on the canister. The effect may instead be uneven deformation of the buffer. In order for the effect to be of importance for canister integrity, shear movements on the order of 0.1 metre are required. With the stresses that prevail in the base scenario, a prerequisite for such a large shear movement is that the deposition hole intersect the central portions of a fracture with a extension of more than a hundred metres. Furthermore, the process of local failures at irregularities in the fracture surfaces must take place in large parts of the fracture plane, which means that parts of the fracture located at a great distance from the stress concentrations around the cavities, i.e. in the undisturbed rock, must also be affected. There is no evidence that such a process could take place. The stress growth that can result from large-scale tectonic movements, and that could reinforce the effect, is much too small to significantly affect the current state of stress during the next 100,000 years.

8.8.4 Confidence, canister analyses

Process understanding

The fundamental understanding of strength and deformations in the canister materials is good.

Models and data

Confidence in models and data is deemed to be sufficient for the calculations presented in the base scenario. The analyses may need to be expanded to include inhomogeneous material properties as well, which can occur as a result of e.g. casting defects in the iron insert. Calculations of creep movements also need to be revised as data on the actual canister material become available.

8.8.5 Confidence, geosphere analyses

Process understanding

The fundamental understanding of the processes and conditions in the surroundings that control the mechanical evolution of the repository is not complete. This applies particularly to time-dependent deformations. However, our understanding is fully adequate for judging the mechanical evolution and stability in the base scenario if pessimistic approximations are employed.

Models

Adequate numerical models are available for some processes which describe the mechanical behaviour of rock and rock masses and can be applied on both the near-field scale and the repository scale for the load cases that occur in the base scenario. There are as yet no fully applicable and validated models for time-dependent deformations and formation of new fractures. Rock-mechanical models are generally used to improve process understanding and to set bounds on the movements and deformations that may have a bearing on the safety of the repository, rather than to make accurate predictions.

Data

Accurate values exist for most rock-mechanical properties on the laboratory scale, but when the data are upscaled to large rock volumes the uncertainties can become considerable. Rock stress data from the field can also have considerable uncertainties. However, the data quality is fully adequate for the schematic and bounding type of analysis on which the conclusions in the base scenario are based.

8.8.6 Conclusions

In summary, the long-term stability of the rock is judged in the base scenario to be such that no rock movements of an extent that could lead to canister failure will take place during the next 100,000 years. Rough calculations show that much larger shear stresses and stress levels than those that generally prevail in the Swedish bedrock at approximately 500 m depth would be required for creep movements or load changes caused by large-scale tectonic movements, individually or in aggregate, to lead to canister failure. There is nothing to indicate that a million-year perspective would not result in the same assessment.

This assessment also applies to the three repository sites Aberg, Beberg and Ceberg, where conditions do not deviate significantly from conditions in the rest of the Swedish bedrock.

Nor do the groundwater or swelling pressures (evenly or unevenly distributed) which can occur in the base scenario give rise to loads that could threaten the canister's integrity.

The base scenario, and thereby its conclusions, does not cover earthquakes, see further Chapter 11.

8.9 Chemical evolution

8.9.1 Overview

The interior of the canister is chemically isolated from its surroundings as long as the copper canister remains intact. The chemical evolution in buffer, backfill and rock is ultimately determined by the composition of the groundwater. In the long term, the chemical properties of the groundwater, together with the properties of the buffer and the copper canister, determine how long buffer and canister will function.

Chemical processes

The following is a summary from the Process Report of the descriptions of the chemical processes that have a bearing on the base scenario.

The post-closure chemical evolution in the **geosphere** around the repository is determined by a number of transport and reaction processes. The predominant transport process is advection, but diffusion also plays a role. Reactions occur between the groundwater and fracture surfaces in the form of dissolution/precipitation of fracture-filling minerals and, very slowly, between the groundwater and the minerals in the rock matrix. In the groundwater, microbial processes, decomposition of inorganic materials from repository construction, colloid formation and gas formation/dissolution take place.

Buffer and geosphere interact chemically by exchange of solutes. Of particular importance is the flow from geosphere to buffer of substances that can damage the buffer or canister (copper corrodants).

The chemical evolution in the **buffer** is also determined by transport and reaction processes. Together they determine the chemical evolution in the buffer.

After water saturation, the predominant transport process is diffusion. Advection can also occur during the saturation process. The most important reactions are ion exchange processes, where ions in the pore water are exchanged for ions in the surface layer of the smectite, chemical degradation of the buffer's montmorillonite component, and dissolution and precipitation of impurities in the buffer. The clay which has intruded into the rock's fracture system during swelling may be eroded in the form of colloids so that the density of the buffer gradually decreases. All of these processes are dealt with in section 8.9.3.

Other reactions are radiation effects, pore water radiolysis, microbial processes and gas formation/dissolution. These processes are deemed to have small effects on the chemical evolution in buffer/backfill (see further the Process Report) and are therefore not dealt with further in the base scenario. The effects of the microbial processes can be neglected if the density of the buffer is maintained, which must be shown in the base scenario.

The canister and buffer interact chemically by exchange of solutes. The flow of copper corrodants from buffer to canister is particularly important.

In the **copper canister**, the chemical evolution is dominated by copper corrosion on the outside of the canister, see section 8.9.4. Furthermore, stress corrosion cracking, material changes due to radiation effects and grain growth can occur. The first two processes are deemed to have small effects on the chemical evolution and safety in the base scenario (see the Process Report) and are therefore not dealt with further. Grain growth has been discussed by Pettersson /1996/, who drew the conclusion that grain growth in the copper canister will be negligible.

In the **cast iron insert**, stress corrosion cracking and material changes due to radiation effects occur. These two processes are deemed to have small effects on the chemical evolution and safety in the base scenario (see the Process Report) and are therefore not dealt with further.

Inside the isolated canister in the **fuel**, radiolysis of residual gas and helium production occur, the latter as a consequence of the fact that alpha particles (helium nuclei) from radioactive decay absorb electrons and form helium. These two processes are deemed to have small effects on the chemical evolution in the base scenario and are therefore not dealt with further (see the Process Report).

Couplings to other aspects of repository evolution

The chemical evolution of the repository is influenced by the thermal evolution due to the fact that diffusion and all reaction processes are dependent on the temperature. The chemical evolution is also strongly influenced by the hydraulic evolution via advection in the geosphere. Some radiation-induced chemical processes of minor importance also occur, i.e. the radiation-related evolution has some influence. The ion exchange process in buffer/backfill can have an appreciable influence on swelling.

What needs to be shown in the base scenario?

A more detailed description of the following aspects of the chemical evolution of the repository is given in coming sections:

- The long-term evolution of groundwater composition in Aberg, Beberg and Ceberg.
- The chemical evolution of the buffer on the three sites.
- Corrosion of the copper canister on the three sites.

Table 8-6 summarizes the most important processes in canister and buffer/backfill which are directly coupled to safety and which are influenced by the composition of the geosphere's groundwater and the buffer's pore water in the base scenario. The table also shows what conditions in groundwater and pore water are desirable from a safety viewpoint.

Table 8-6. Overview of important processes influenced by the composition of pore water and groundwater.

Process	Component/variable	"Preference"/comment
Copper corrosion	Dissolved oxygen	Oxygen-free (indicated by negative Eh values)
	Sulphide	The lower the better
	Combination chloride ions/pH	Avoid the combination $[Cl^-] > 100$ g/l and pH < 3
Swelling	Total salinity	Below 100 g/litre*
Smectite degradation (illitization)	Potassium	The lower the better
Colloid formation/ erosion of buffer	Divalent cations, mainly Ca^{2+} och Mg^{2+}	$[Ca^{2+} + Mg^{2+}] > 4$ mg/l

* The backfill is more sensitive than the buffer in this respect. The composition of the backfill will be adapted to e.g. the salinity on the site. This is not done in SR 97, however.

Importance for safety

The chemical evolution of the repository may have a direct bearing on safety, since corrosion of the canister could influence its isolating capacity. Furthermore, buffer function is influenced by chemical changes. In the long term, the chemical properties of the groundwater, along with the properties of the buffer and the copper canister, determine how long buffer and canister will function.

8.9.2 Long-term evolution of groundwater composition

Introduction

The geochemical situation in Swedish bedrock is generally very stable. Reaction and transport processes proceed constantly, but generally lead only to very slow changes. Reactions occur between different components in the groundwater, between water and fracture-filling minerals and between water and rock matrix. The groundwater flow transports reactants and reaction products to and from the reactions. The flowing groundwater also causes a mixing of different groundwater types from different parts of the geosphere.

The frames for this evolution are defined by inflow and outflow of water from/to the biosphere, and by exchange with very deep-lying groundwater. The evolution is thereby controlled by e.g. precipitation quantities and near-surface chemical conditions. The geochemical evolution on a repository site is thus determined by:

- The present-day geochemical situation.
- Transport and reaction processes in the geosphere.
- Interaction with the surroundings, above all inflows and outflows from/to the biosphere, which are in turn dependent on the climate.

Similarly, the present-day geochemical situation is the result of past climatic conditions and transport and reaction processes.

Major changes in the chemical composition of the groundwater are caused primarily by long-term climate change, which leads to changes in precipitation and above all flow conditions, which can in turn lead to noticeable effects on the composition of the groundwater. Effects of climate change are discussed in the climate scenario. In the base scenario, land uplift in particular has long-term effects on flow patterns and thereby on groundwater composition.

Table 8-6 above shows that total salinity, concentrations of potassium, calcium, magnesium, chloride, sulphide and dissolved oxygen, and redox potential (Eh) and pH have a direct bearing on safety. Several of these – above all pH, Eh and salinity – are furthermore necessary for a general understanding of the geochemical conditions. In addition, an understanding of radionuclide transport requires knowledge of fulvic and humic acids, colloid concentrations and microbes.

Interaction with surroundings

The hydrogeochemical situation on a site is influenced by flow pattern and groundwater composition in the surrounding region. The range of influence can vary widely between different sites.

Large-scale flow systems have been modelled numerically and indicated flow patterns which vary considerably between the sites, see section 8.7.2. The upward-directed flow situation at Aberg is compatible with the relatively high salinity at repository depth, which would be a consequence of the upward transport of deeper groundwater with a higher salinity. At great depth, the groundwater at Aberg is extremely saline and has moreover been isolated from the atmosphere for millions of years /Laaksoharju and Wallin, 1997/. Indirectly, it can be said that the downward-directed flow situation in Ceberg is also confirmed hydrochemically by the fact that no saline water has been encountered at repository depth.

Initial state

The description of the hydrochemical evolution is based on a review of all water samples from each site, see Laaksoharju et al /1998/. The reference waters should thereby reflect the present-day natural water composition at repository depth. The material includes 483 water samples from Aberg, 37 from Beberg and 11 from Ceberg. The spatial variability of the water composition is thereby relatively well-known in Aberg, while it is much less well-known in both Beberg and Ceberg. Reference waters are reported in the column "undisturbed state" in Table 8-7, Table 8-8 and Table 8-9 for Aberg, Beberg and Ceberg, respectively.

There is no significant correlation between rock types and water composition on the three sites. In Aberg there is a correlation between water composition and permeability when different measurement points are compared.

Based on assessments of previous groundwater compositions and climatic conditions, the historic evolution of groundwater composition has been reconstructed /Laaksoharju and Wallin, 1997/. It has been possible to explain present-day hydrochemical conditions on the three sites with the aid of principal component analysis and subsequent mixing calculations /Laaksoharju et al, 1998/.

Construction and operation of the repository will alter the hydrochemical conditions due to the increased water flow in the rock and the chemical influence of engineering and stray materials from construction. These changes are judged to be short-lived in relation to the projected life of the repository. The original conditions can be expected to be reinstated within approximately 100 years of closure. However, experience from underground facilities shows wide variations in the time required to restore original conditions, see section 8.7.2.

Long-term evolution at Aberg

The long-term evolution of a site can be described on the basis of general knowledge of the evolution of its water chemistry from far in the past up to the present. On each site, this evolution is controlled by the hydraulic driving forces and variations in the permeability of the rock and the distribution of saline and non-saline water. The evolution is influenced by land uplift at all sites.

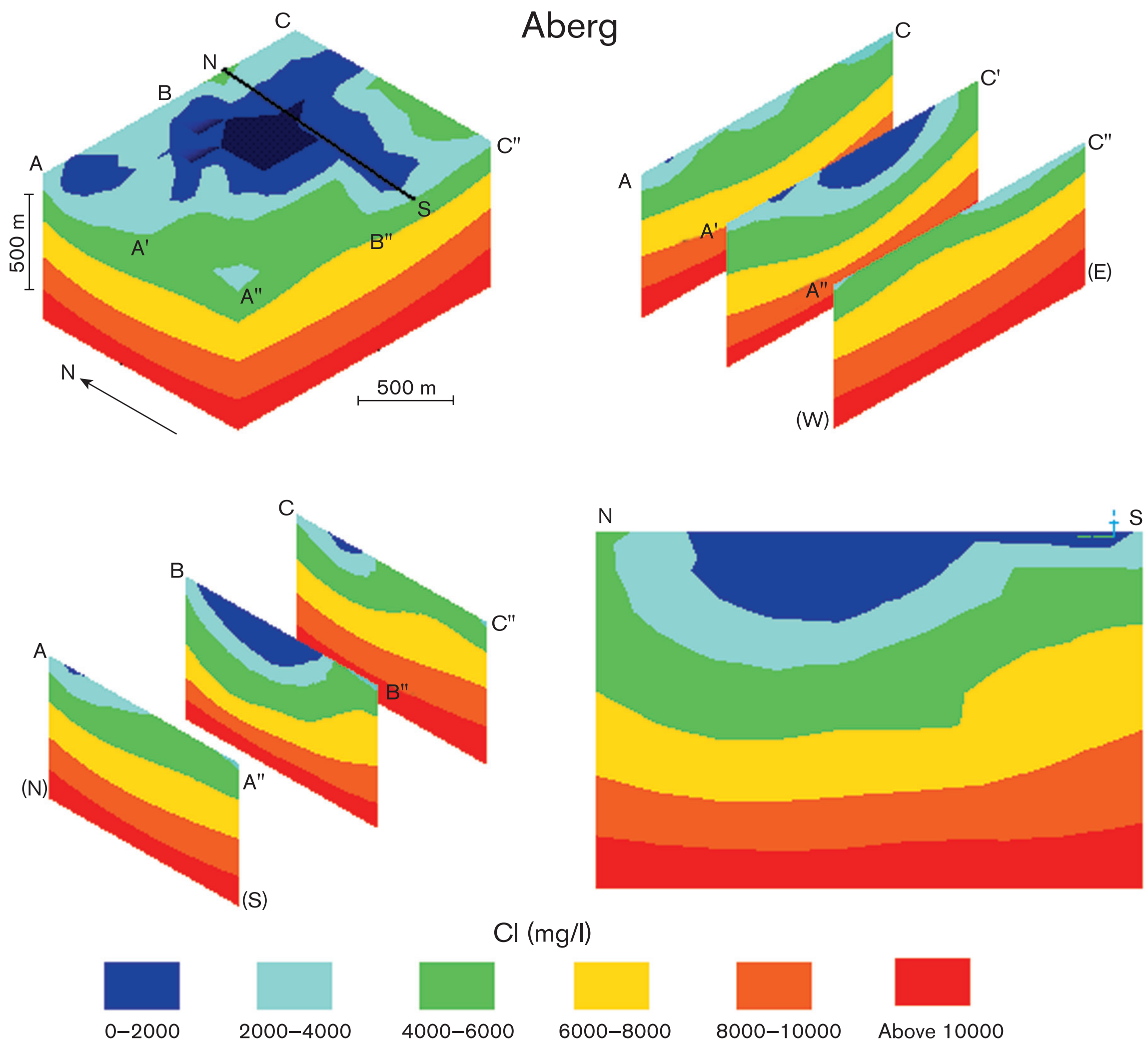

Figure 8-25. *Salinity distribution in Aberg based on kriging (interpolation) of measured chloride concentrations in boreholes.*

The present day groundwater in Aberg is derived from different periods before and after the most recent deglaciation. Figure 8-25 illustrates the salinity distribution in Aberg. Meteoric water has infiltrated the bedrock down to a depth of 100 metres and washed out earlier saline water. This is judged to have happened during the past three thousand years as an effect of the ongoing land uplift. At greater depths there are traces of modern and older Baltic Sea water, glacial meltwater and at great depth saline water that originates from the rock /Rhén et al, 1997b/.

During repository operation, non-saline water is expected to be drawn into the repository from above, Baltic Sea water from the sides and saline water from below. The salinity distribution is thereby expected to be affected to some extent and the mixing proportions will be changed. Local variations are expected to be great and dependent on the direction of the flow paths. During this period, saline water can be expected to be drawn up from below and cause a salinity increase of 50–100 percent. At other points, non-saline water may infiltrate at repository level and lower the concentrations appreciably. Similar effects have been observed in the Äspö HRL as a consequence of the drawdown caused by the facility /Rhén et al, 1997a; Rhén et al, 1997b/. Original conditions are expected to be reinstated as soon as the original flow and pressure conditions have been restored, i.e. after about 100 years.

During this period, engineering and stray materials from construction may influence the water composition in the repository.

Organic material and entrapped oxygen will react. Initially, entrapped oxygen will be consumed by aerobic bacterial. All oxygen is projected to be consumed within a few years /Puigdomenech et al, 1999/. Subsequently, ferric iron in fracture-filling minerals is expected to be converted to dissolved ferrous iron by iron-reducing bacteria if organic material is still present. If degradable organic material is still present after that, sulphate in the groundwater is expected to be reduced to sulphide. The effects of the biological processes will be that the carbonate content of the water will increase in proportion to the quantity of degraded organic material in the cycled water volume. This will also cause a decline in pH to around 7 or just below. The increased carbonate content may lead to formation of a new calcite layer on the fracture surfaces, but if the pH falls sharply it may also lead to a dissolution of calcite from the fracture surfaces. In a somewhat longer time perspective, feldspar weathering will also have an influence.

Theoretically, bacterial sulphate reduction can reduce all sulphate to sulphide. The sulphide concentration of the reference water in Aberg may then increase to 180 mg/l. This is limited by the amount of degradable organic material available, which under undisturbed conditions is estimated to be less than 10 mg/l, but which during the post-closure resaturation phase can be expected to amount to on the order of 100 mg/l. The sulphide that is formed will furthermore be precipitated, among other things as iron sulphide so that the sulphide concentration will probably be limited to less than 10 mg/l. In most cases the sulphide concentrations are below 1 mg/l. This is true of the chosen reference waters /Laaksoharju et al, 1998/.

The iron sulphide formed and other sulphide precipitations constitute a buffer against oxidation. Experiments and calculations have shown that even under a forced inflow, which could occur e.g. when a continental ice sheet melts, the dissolved oxygen disappears quickly /Puigdomenech et al, 1999; Guimera et al, 1999/.

The degradation of inorganic material, primarily concrete and steel in engineering materials, is not deemed to be of any importance for the water chemistry as a whole in the rock volume around the repository. The cement groutings done during the construction of the Äspö tunnel could only be traced in the form of elevated pH for a few days /Rhén et al, 1997a/. Cement and concrete near deposition holes may raise the pH locally and more durably.

As a result of the process of postglacial land uplift (crustal upwarping), Aberg is gradually being transformed from an island to a part of the mainland coast, where infiltrating groundwater will wash out more and more of the saline groundwater. A sharper boundary between non-saline and saline water will then probably arise. If it is assumed that the present-day infiltration pattern is constant and that meteoric water has washed the groundwater clean to a depth of 100 m over the past three thousand years, it is expected to take at least five times as long to wash clean to a depth of 500 m, presumably much longer. The sharper the transition between non-saline and saline water becomes, the slower the washing-out process becomes; and the deeper the boundary lies, the smaller the flow that can drive out the saline water becomes. When Aberg changes from being an island to being part of the mainland, the hydraulic driving force will increase. This is expected to occur in about 2,000 years, and the boundary between saline and non-saline water is then projected to lie at a depth of about 150 m. The reference water for Aberg should therefore be representative for the next 100 to 10,000 years. After that, salinity is projected to decline as the proportion of meteoric fresh water increases, at which point

Table 8-7. Possible hydrochemical conditions in Aberg at different times. The reference water composition for Aberg is given as the undisturbed state.

Component/ variable	Undisturbed state	At closure	In the future; 10,000–100,000 years after closure
pH	7.7	6–8	8–9
Eh (mV)	–308	0 till –400	–200 till –300
Na^+ (mg/l)	2,100	1,000–3,000	100–2,000
K^+ (mg/l)	8	5–20	2–10
Ca^{2+} (mg/l)	1,890	1,000–3,000	20–2,000
Mg^{2+} (mg/l)	42	10–200	1–40
HCO_3^- (mg/l)	10	10–1,000	10–20
Cl^- (mg/l)	6,410	3,000–10,000	200–5,000
SO_4^{2-} (mg/l)	560	100–600	1–400
HS^- (mg/l)	0.15	0–10	0–1
Colloids (mg/l)	0.05*	1–100	< 0.5
Fulvic- and humic acids (mg/l)	0.1*	0–10	< 0.5

* A specific measurement result for the sampled level is lacking. The value is a general estimate for deep groundwaters in Sweden.

the composition of the water would then approach that of the reference water in Ceberg, see below. In such a dynamic situation, there will undoubtedly exist isolated volumes where the exchange takes place much more slowly, perhaps taking 100,000 years. The proportion of such volumes cannot be predicted today.

Table 8-7 summarizes possible hydrochemical conditions in Aberg at different times. "Undisturbed state" refers to the situation before repository construction and the expected situation 100–10,000 years after closure. The column shows the composition of the reference water for Aberg /Laaksoharju et al, 1998/. "At closure" refers to the period up to 100 years after closure and is an expert assessment of changes before and after closure based on knowledge of conditions in the Äspö HRL before, during and after the tunnel construction phase /Rhén et al, 1997b/; "In the future" refers to the period 10,000–100,000 years after closure, based on an evolution towards today's situation in Ceberg.

The concentration of organic material is very high during the period after closure, tens to perhaps hundreds of mg/l. After that it is projected to decrease to around 1 mg/l within a few years. The colloid concentration can be estimated at tens of mg/l after closure, whereupon it will decline to less than 0.5 mg/l after a few years.

Equilibrium calculations with the program WATEQ /Laaksoharju et al, 1998/ show that the water composition is in equilibrium with the minerals calcite, gypsum, quartz, hematite, goethite and iron sulphide. This means that the Eh is determined by both the iron and sulphide systems at the same time, i.e. both the systems are in equilibrium. This shows that the hydrochemistry is as stable as can be expected and thereby that no large-scale mineral dissolutions and precipitations are occurring, and that the body of data is reliable.

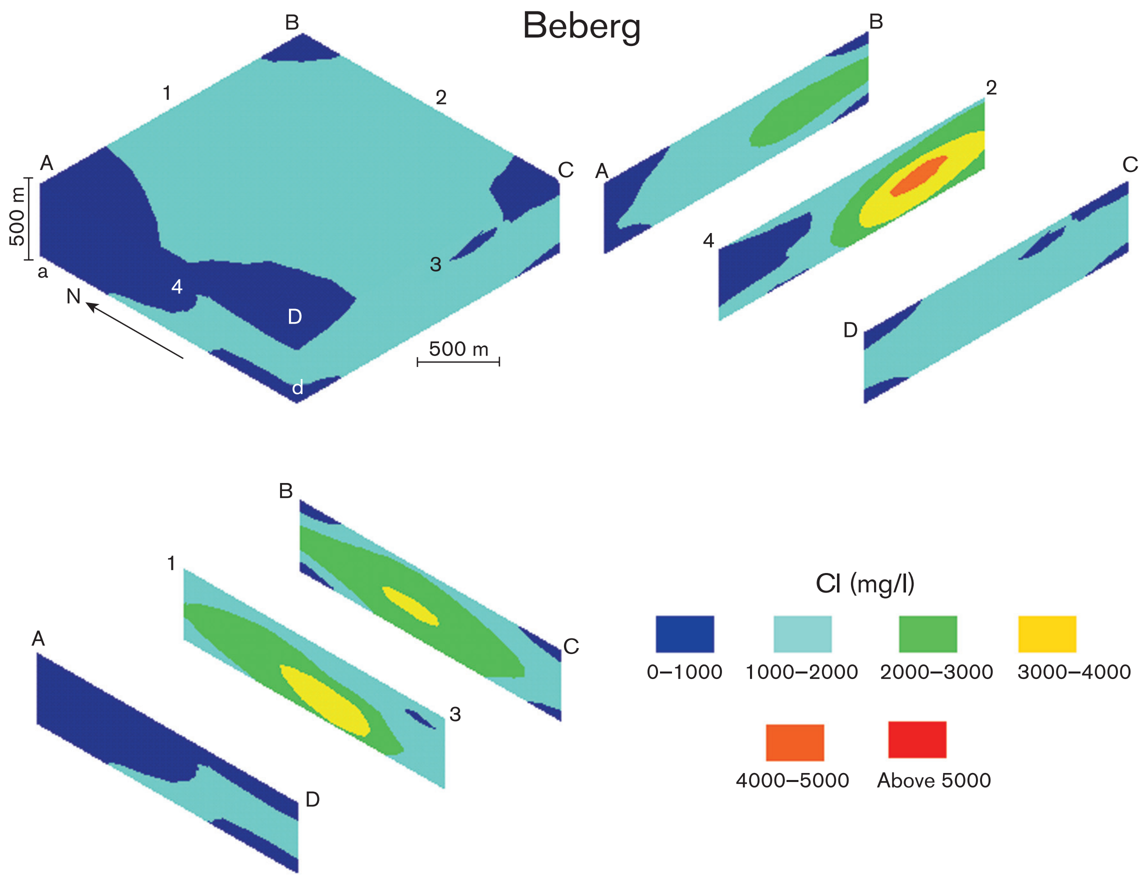

Figure 8-26. *Salinity distribution in Beberg, based on kriging (interpolation) of measured chloride concentrations in boreholes.*

Long-term evolution at Beberg

Saline and non-saline water occur in a complex pattern in Beberg. Figure 8-26 shows the salinity distribution in the rock volume.

Beberg is in a situation today that is expected to exist in Aberg in a thousand years or so. The heterogeneous salinity distribution in Beberg contrasts with the relatively homogeneous distribution in Aberg. If Beberg had undergone a similar evolution as that sketched for Aberg, saline water would occur generally at depth in Beberg as well. In fact, it occurs in one part of the area but not in the other. This may be an effect of prevailing hydrological and structural properties at Beberg whereby a washing-out of saline water has gone much deeper in one part of the area. Since the body of data for Beberg is much smaller than for Aberg, the possibility cannot be ruled out that there is saline water at depth in the non-saline water part as well. If this was the case, conditions in Beberg would also confirm the impression from Aberg, namely that the washing-out of saline water proceeds very slowly.

At present there is both saline and non-saline water in Beberg. After a repository has been built and stood open for 50 years, there will probably only be either non-saline or saline water left. Both possibilities are reasonable, and therefore two reference waters have been defined /Laaksoharju et al, 1998/. Most likely, the water below repository level will be saline and this water will be drawn up to the repository. It is then expected to sink back during the first 100 years after closure.

Table 8-8. Possible hydrochemical conditions in Beberg. The composition of the saline and non-saline reference water for Beberg is given as the undisturbed state.

Component/ variable	Undisturbed state saline/non-saline	At closure	In the future; 10,000–100,000 year after closure
pH	7.0/7.9	6–8	7–9
Eh (mV)	–200*/–250	0 to –400	–200 to –300
Na^+ (mg/l)	1,700/275	300–2,000	100–1,000
K^+ (mg/l)	13/2	2–13	2–10
Ca^{2+} (mg/l)	1,650/142	150–1 650	20–1,000
Mg^{2+} (mg/l)	110/17	17–110	4–100
HCO_3^- (mg/l)	47/278	50–300	20–40
Cl^- (mg/l)	5,500/555	500–5,000	200–5,000
SO_4^{2-} (mg/l)	370/49	40–400	1–400
HS^- (mg/l)	<0.01/–	0–10	0–1
Colloids (mg/l)	0.05*	0–100	< 0.5
Fulvic- and humic acids (mg/l)	0.1*	0–10	< 0.5

* A specific measurement result at the sampled level is lacking. The value is a general estimate for deep groundwaters in Sweden.

Organic and inorganic engineering and stray materials are expected to be degraded/consumed in the same way as at Aberg during the initial 100 years of the repository's lifetime.

Table 8-8 summarizes possible hydrochemical conditions in Beberg at different times. "Undisturbed state" refers to the situation before repository construction and the expected situation 100–10,000 years after closure. The column shows the composition of saline and non-saline reference water for Beberg /Laaksoharju et al, 1998/. "At closure" refers to the period up to 100 years after closure and is an expert assessment of changes before and after closure based on knowledge of conditions in the Äspö HRL before, during and after the tunnel construction phase /Rhén et al, 1997b/; "In the future" refers to the period 10,000–100,000 years after closure, based on an evolution towards today's situation in Ceberg.

The concentration of dissolved organic material in Beberg is significantly higher than in Aberg and Ceberg. The concentration of 5.7 mg/l may be due to contamination in conjunction with drilling and borehole investigations, but may also be a correct value. The maximum value for colloid concentrations given in SKB-91 was 0.4 mg/l. More recent detailed studies of colloids have shown that the levels can generally lie below 0.05 mg/l in undisturbed granitic groundwaters /Laaksoharju et al, 1995/.

Equilibrium calculations with the program code WATEQ /Laaksoharju et al, 1998/ show that the water composition is in equilibrium with the minerals calcite, gypsum, quartz, fluorite, hematite and goethite. Iron sulphide is greatly undersaturated, which indicates disturbances in conjunction with the investigations, which were conducted in the early 1980s. Siderite is undersaturated in a similar manner as in Aberg. It can thereby be claimed that the mineral phases that reach rapid equilibrium show that the saline typical water in Beberg has a stable composition and can be regarded as being representative of prevailing conditions. The Eh is estimated with the aid of the water's iron content and pH, since a measurement result is lacking.

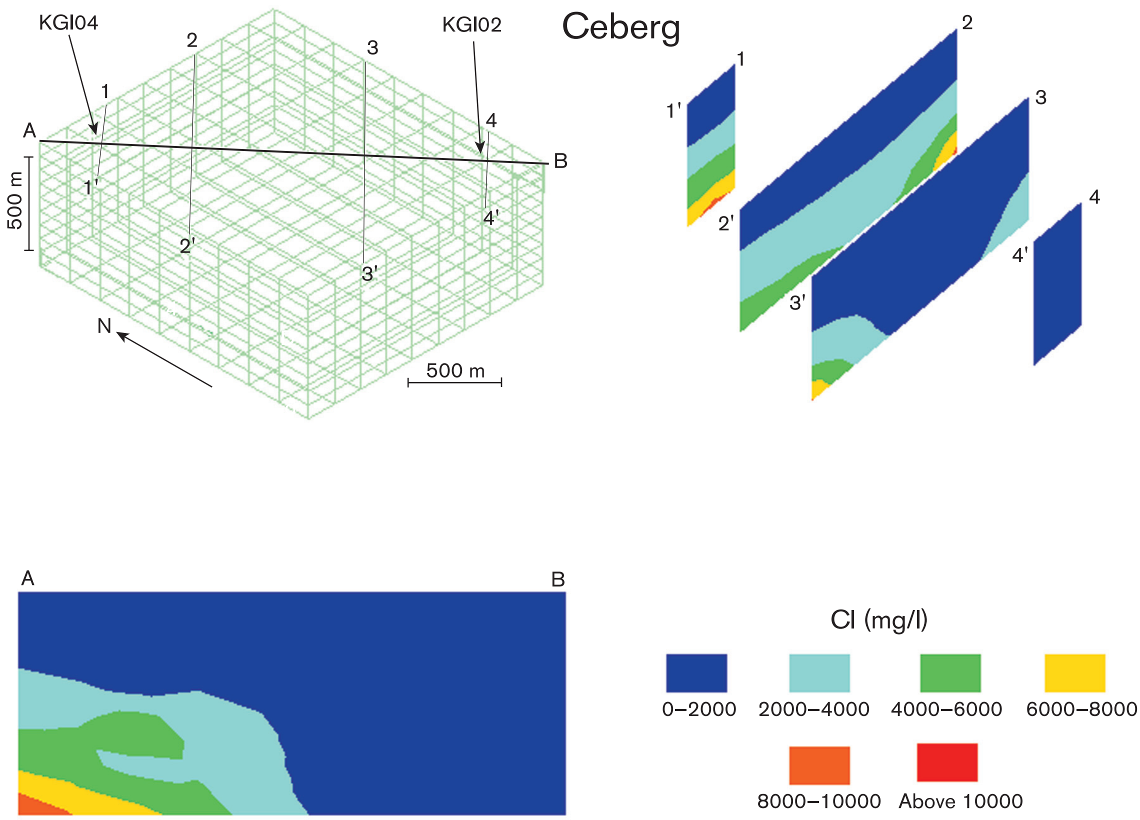

Figure 8-27. *Salinity distribution in Ceberg, based on kriging (interpolation) of measured chloride concentrations in boreholes.*

Long-term evolution at Ceberg

Ceberg is situated on the highest coastline and has been subjected to inflow and outflow of infiltrating groundwater for the longest time of the three sites. There has probably not been saline water in Ceberg since the most recent ice age. This means that the groundwater ought to have obtained its chemical character by interaction between water and rock. However, this does not mean that the water has infiltrated at the ground surface and then descended to greater depth as a unified front. Mixing occurs and has occurred in various contexts, but all water has a meteoric origin. The salinity distribution in Ceberg is illustrated in Figure 8-27.

During operation of the repository, more near-surface water will be drawn down into the rock. Since the character of superficial and deep water in Ceberg is relatively similar, this is not expected to alter the water composition significantly. After closure, conditions will return to the initial state at a rate determined by the influx of regional water from north and west, see section 8.7.2.

Nor will the long-term evolution affect the water chemistry appreciably. Since the groundwater is already of meteoric origin now, land uplift will be of no importance for the hydrochemical evolution.

Organic and inorganic engineering and stray materials are expected to be degraded/ consumed in the same way as at Aberg during the initial 100 years of the repository's lifetime. Sulphate reduction is not expected to occur in Ceberg, however, since the sulphate concentrations are so low.

Table 8-9. Possible hydrochemical conditions in Ceberg. The reference water composition for Ceberg is given as the undisturbed state.

Component/ variable	Undisturbed state	At closure	In the future; 10,000–100,000 years after closure
pH	9.3	7–9	8–10
Eh (mV)	–200	0 till –400	–200 ± 100
Na^+ (mg/l)	100	10–100	100 ± 50
K^+ (mg/l)	2	1–10	5–0
Ca^{2+} (mg/l)	21	1–20	10–20
Mg^{2+} (mg/l)	1	1–5	1–5
HCO_3^- (mg/l)	18	10–100	10–20
Cl^- (mg/l)	180	20–200	100–200
SO_4^{2-} (mg/l)	0.1	0.1–10	0.1–1
HS^- (mg/l)	< 0.01	0–1	0.1–1
Colloids (mg/l)	0.05*	1–100	< 0.5
Fulvic- and humic acids (mg/l)	0.1*	0–10	< 0.5

* A specific measurement result at the sampled level is lacking. The value is a general estimate for deep groundwaters in Sweden.

Tabell 8-9 summarizes possible hydrochemical conditions in Ceberg at different times. “Undisturbed state” refers to the situation before repository construction and the expected situation 100–10,000 years after closure. The column shows the composition of the reference water for Ceberg /Laaksoharju et al, 1998/. “At closure” refers to the period up to 100 years after closure and is an expert assessment of changes before and after closure based on knowledge of conditions in the Äspö HRL before, during and after the tunnel construction phase /Rhén et al, 1997b/; “In the future” refers to the period 10,000–100,000 years after closure, based on an evolution whereby the present-day situation in Ceberg is more or less perpetuated.

Equilibrium calculations with the program code WATEQ /Laaksoharju et al, 1998/ show that the water composition is in equilibrium with calcite, siderite, fluorite, quartz, amorphous iron hydroxide and iron sulphide. The water is oversaturated with respect to goethite and hematite and greatly undersaturated with respect to gypsum. This indicates some disturbance in conjunction with drilling and/or sampling. The redox conditions have been calculated on the basis of pH and iron(II) concentrations. The oversaturation with respect to goethite and hematite suggests oxygen intrusion in conjunction with sampling or earlier borehole activities.

Long-term redox conditions

One of the fundamental criteria for repository safety is that the groundwater should be free of dissolved oxygen. The oxygen concentration in infiltrating rainwater is approximately 10 mg/l. The oxygen is consumed as the water passes through the soil layer before it reaches down to the rock. If the soil layer is thin or non-existent, oxygenated water will reach down into the rock’s fracture system. Here as well, the oxygen is consumed completely in biological processes and in reactions with the rock’s iron-containing minerals /Puigdomenech et al, 1999/. There are no indications that iron(II) minerals have been oxidized by oxygenated groundwater anywhere at repository depth /Gascoyne, 1999; Guimera et al, 1999/. However, this does not mean that iron(III) minerals are absent at great depth. Hematite occurs widely in fracture-healing minerals and is the result of oxidation under hydrothermal conditions, when water has oxidized iron without any dissolved oxygen.

Quality assessment of the reference waters

The reliability of the chosen reference waters varies. In general, the water samples taken more recently have higher reliability (are more representative) than those taken earlier. A quality measure has been developed on the basis of a semiquantitative assessment system developed in cooperation with TVO (now Posiva). The measure indicates the representativeness of the water sample in relation to all those included in the evaluation (which can be said to be typical for Swedish-Finnish granitic bedrock). The various steps in the investigation sequence are assessed and graded with regard to how well they have been performed in each case /Laaksoharju et al, 1993/. Examples of questions to which the answers have been graded are: How much drilling water has been used in drilling through the sampled section? How strong a draw-down has been cost by the sampling? How long has the sample remained in hoses and bottles before analysis? Which method has been used for the analysis? etc. The median value obtained for all the Swedish and Finnish water samples included in the evaluation is zero. A positive value thereby indicates a higher representativeness (reliability), while a negative value indicates a lower representativeness than the median for all the samplings done in SKB's and Posiva's site investigations.

The value for the reference water at Aberg is 0.86, at Beberg 0.63 (saline) and –0.36 (non-saline), and at Ceberg –0.15. This means that the representativeness of the Aberg water and the saline Beberg water is high, while it is lower for Ceberg and especially for the non-saline reference water in Beberg.

Uncertainties

Uncertainties in the geochemical model description are discussed in the Data Report:

- Disturbances at the time of measurement due to tunnel construction or facility operation alter the flow pattern around the repository, entailing a risk of introduction of more saline groundwater from lower depths in the bedrock. (This situation is exploited to ascertain what conditions can be expected to prevail at closure.)
- Measurement error in analysis of main components (Na^+, K^+, Mg^{2+}, HCO_3^-, Cl) is on the order of 1–5 percent and pH can vary by up to one unit.
- The effect of future groundwater movements due to land uplift will influence the current water chemistry. Salinities in particular are expected to change as the shoreline is displaced.
- The influence of engineered barriers (bentonite) may alter the water composition, but only very little in relation to the changes assumed to occur as a consequence of altered flow regimes around the open repository.

It is reasonable to assume that the uncertainty in groundwater chemistry, both its spatial variations and future evolution, is largely limited by the variation between the four reference waters used in SR 97.

8.9.3 Chemical evolution of buffer/backfill

Processes

The buffer material, MX-80 bentonite, consists of approximately 75 percent montmorillonite and sodium as the dominant sorbed cation, plus approximately 25 percent other minerals (impurities), where quartz and feldspar dominate. MX-80 also contains small amounts of calcite and pyrite, and these impurities may be of importance for the chemical environment in the repository.

A number of chemical processes in the buffer/backfill will eventually alter the composition of the buffer and backfill. The processes may thereby also be of importance for the properties of the buffer/backfill.

The chemical processes that have been identified in buffer/backfill which may be of long-term importance are:

- Ion exchange in the montmorillonite, principally between Ca^{2+} and Na^{+}; ion exchange with protons may also be of importance.
- Dissolution of impurities in the bentonite.
- Conversion of the montmorillonite to non-swelling minerals.
- Precipitation of minerals caused by the temperature gradient.

The processes are described in detail in the Process Report. In this section, the descriptions are summarized and the processes are quantified with site-specific model calculations or simpler approximations.

Furthermore, the probability of long-term erosion of the buffer is discussed, i.e. that buffer material intruding into fractures around deposition holes may be carried away with the groundwater. Finally, the effects if a water with a much higher ionic strength than those expected on the three analyzed sites should enter the repository are analyzed. Such a situation is not likely in the base scenario, but is nevertheless discussed as an extreme variant.

Long-term impact on function

The chemical evolution can have a long-term impact on many properties of the buffer and backfill.

The buffer's primary function is to constitute a diffusion barrier between canister and rock. This requires a low hydraulic conductivity and the ability to keep the canister centred in the deposition hole for a long time. This in turn makes demands on density and swelling pressure, see section 5.7. The backfill is subject to criteria for hydraulic conductivity and swelling pressure.

The following can be said of the processes described in this section for both buffer and backfill:

- hydraulic conductivity and swelling pressure are influenced by ion exchange, mineral precipitation, mineral conversion and erosion,
- density is influenced by erosion.

Ion exchange

Montmorillonite (MX-80) initially has approximately 80 percent sodium in the ion exchange positions. In general, divalent ions are bound more tightly to the montmorillonite than univalent ones. Granitic groundwaters generally have a higher Ca/Na ratio than that which prevailed when the bentonite was formed. This means that calcium can be expected to change place with sodium when the bentonite comes into contact with groundwater. The time it takes to convert most of the Na-montmorillonite to Ca-montmorillonite depends on the groundwater's composition, the concentration of calcium-containing impurities in the buffer, and the water composition in the near field.

Bruno et al /1999/ use an ion exchange model to calculate the conversion from Na- to Ca-montmorillonite for the three reference waters in SR 97. In the model it is assumed that the buffer is saturated with the site-specific groundwater and that the montmorillonite with impurities is immediately equilibrated with the pore water, causing the pH to fall and the carbonate content to rise. The pore water is then continuously replaced by the site-specific groundwater.

It has been assumed in the calculations that the pore water in the buffer is completely exchanged in 10,000 years in all cases. A water turnover time of 10,000 years corresponds to a groundwater flux in the rock of approximately 10^{-4} $m^3/(m^2 \cdot y)$, which corresponds roughly to the conditions in Ceberg. An increase in the flow by an order of magnitude (corresponds to Aberg and Beberg) would give a turnover time of 3,000 years /KBS-3/.

The model includes ion exchange between the cations in the penetrating water and those that were originally bound to the montmorillonite surfaces, plus input of calcium ions from dissolution of calcite impurities in the bentonite. Table 8-10 shows the most important properties of the groundwater used in the calculations. The non-saline water, which has a relatively high bicarbonate content, is used for Beberg. The saline water in Beberg is similar to the Aberg water and is therefore expected to give rise to a similar chemical evolution in the buffer.

Figure 8-28 shows the results of the calculations of the ion exchange process.

The ion exchange process goes fastest in Aberg, which has a saline groundwater with a high calcium content: after several hundred thousand years, most of the Na-montmorillonite has been transformed into Ca-montmorillonite. The conversion goes much slower in the reference waters from Beberg and Ceberg, due to lower calcium concentrations. In the Ceberg water, the conversion ceases when all calcite in the buffer has been dissolved, since the Na/Ca ratio in the groundwater is too high for any appreciable ion exchange to take place. The time indication in the figure applies to conditions in Ceberg. In Aberg and Beberg the processes can be expected to proceed approximately three times faster than is indicated in the figures.

In MX-80 bentonite, most of the univalent ions in exchange positions result in great potential swelling, while polyvalent ions and larger univalent ions, such as Cs^+, result in considerably less potential swelling. In the buffer, however, a high swelling capacity will

Table 8-10. Some properties of the groundwaters on the three sites.

	Aberg	Beberg (non-saline)	Ceberg
Ca^{2+} (mg/litre)	1,900	140	21
Na^+ (mg/litre)	2,100	280	110
pH	7.7	7.9	9.3

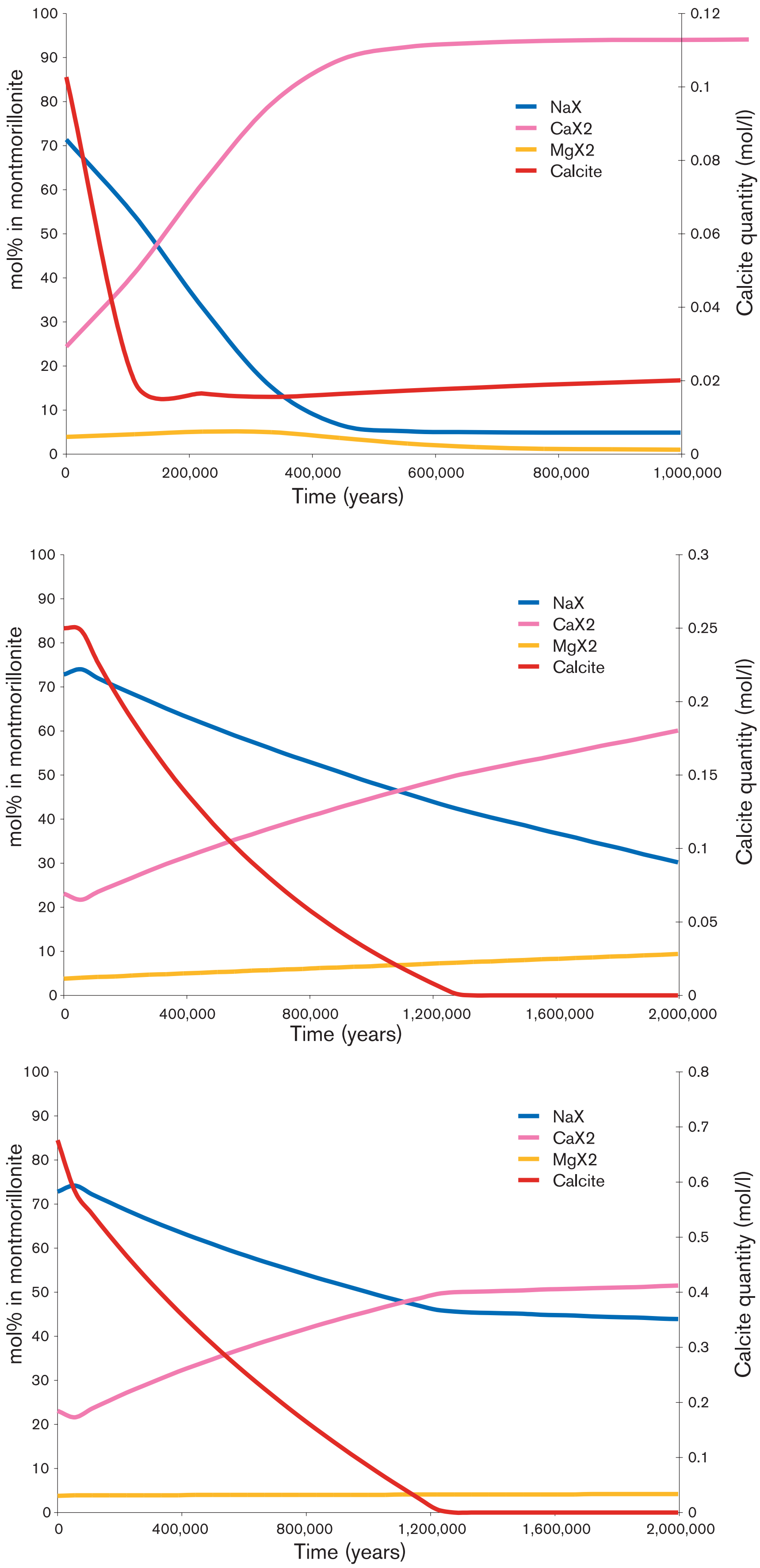

Figure 8-28. Results of the modelling of the ion exchange process on the three sites. The figures show how sodium, calcium and magnesium are distributed in the bentonite's ion exchange positions and how calcite dissolves with time.

be retained even with full conversion to Ca-montmorillonite, due to its high density. A total conversion from Na- to Ca-montmorillonite would lead to a reduction of the swelling pressure from 7–8 MPa to 4–5 MPa /Process Report/. At Aberg, the swelling pressure can thus be expected to decrease to 4–5 MPa in approximately 100,000 years. This is of no importance for the buffer's function, however.

The situation in the backfill is another, the quantity of montmorillonite per unit volume is much lower than in the buffer and a conversion will lead to a loss of swelling pressure. This effect can, however, be compensated for by choosing a higher proportion of bentonite on a site where ion exchange is expected to be extensive. In SR 97 it is assumed that the backfill is site-adapted in such a way that the criteria for conductivity and swelling capacity are met.

Protons are bound to a small fraction of the ion exchange positions. This gives the montmorillonite a pH-buffering capacity. If a water with low pH enters the buffer, protons will be bound, whereas water with a high pH will liberate protons. This buffers the pH towards a neutral value. The pH-buffering effect of calcite impurities is greater, however.

Dissolution of impurities

MX-80 contains approximately 75 percent montmorillonite and 25 percent impurities in the form of other minerals, see section 6.4.12. These are stable in Swedish groundwaters, with a few exceptions:

Pyrite oxidation: Pyrite (FeS_2) is stable in oxygen-free groundwaters. Intruding oxic (oxygen-containing) water can, however, oxidize the pyrite as follows:

$$2FeS_2 + 7\tfrac{1}{2}O_2 + 7H_2O \leftrightarrow 2Fe(OH)_3 + 4SO_4^{2-} + 8H^+$$

The reaction liberates protons and can therefore lower the pH. This reaction is relatively fast and can therefore contribute towards a rapid restoration of reducing conditions in the repository after it has been built and closed.

Calcite dissolution: Calcite ($CaCO_3$) is normally stable in Swedish groundwaters, but the ion exchange process consumes the free calcium ions that are required to prevent calcite dissolution. In the waters from Beberg and Ceberg, all calcite is expected to be dissolved because of this (see Figure 8-28). Calcite is also an effective pH buffer. The reaction

$$CaCO_3 + H_2O \leftrightarrow Ca^{2+} + HCO_3^- + OH^-$$

consumes protons. This is particularly important in an early stage, when oxygen remaining in tunnels and deposition holes oxidizes the pyrite in the buffer, forming protons. Calcite has lower solubility at high temperatures than at low. At an early stage after repository closure, the temperature gradient over the buffer is approximately 30ºC, which could cause calcite in the outer part of the buffer to dissolve and migrate to the warmer inner part and precipitate there.

In the above model study /Bruno et al, 1999/, the way in which calcite dissolution and pyrite oxidation affect pH and redox conditions in the repository's near field is also calculated, integrated with the modelling of the ion exchange process, for the groundwaters at Aberg, Beberg and Ceberg. Two different sets of input data are used in the calculations:

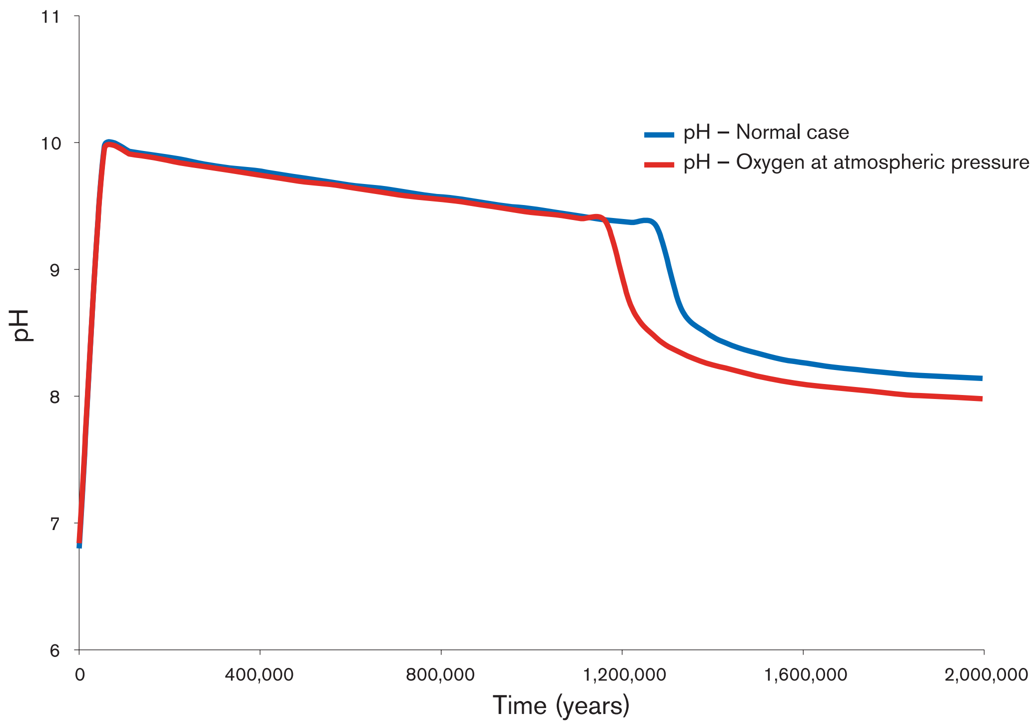

Figure 8-29. *Evolution of pH in buffer in contact with Beberg water.*

- The main case, where the redox potential is given by the reactions between the groundwater and the bentonite.
- A case with oxidizing conditions, where the intruding groundwater is in equilibrium with air at atmospheric pressure. The case reflects the situation directly after repository closure or the effect of direct intrusion of a surface water.

Figure 8-29 shows the results of simulations with the reference water from Beberg. Aberg and Ceberg show the same trends. According to the figure, all cases exhibit an initial decrease in pH to about 7 caused by an initial pyrite oxidation. This decrease is followed by a pH increase to nearly 10 after an exchange with groundwater. The pH is slightly higher in the reference water for Ceberg (10.7), and lower in Aberg. The pH then falls slowly until all calcite in the buffer has been consumed. The pore water then assumes the same pH as the intruding groundwater, i.e. approximately 8 in Beberg.

No oxygen enters the repository in the main case. This means that no pyrite oxidation occurs beyond that due to the initial equilibration. If the intruding water is oxygenated, on the other hand, reducing conditions persist as long as pyrite remains in the buffer. Figures 8-30 and 8-31 show how the pyrite content of the bentonite buffers the redox conditions. The pyrite lasts more than half a million years even if the groundwater is saturated with air at atmospheric pressure.

The changes in pH and redox conditions do not appreciably affect the buffer's hydraulic conductivity or swelling pressure.

Precipitation of minerals caused by the temperature gradient

The temperature in the buffer will initially be about 80ºC at the canister surface and about 60ºC at the rock, see section 8.6. Calcium sulphates (gypsum and anhydrite), as well as calcite, have lower solubility at high temperatures and could "migrate" towards the canister surface. Quartz and other silicon compounds are normally stable under

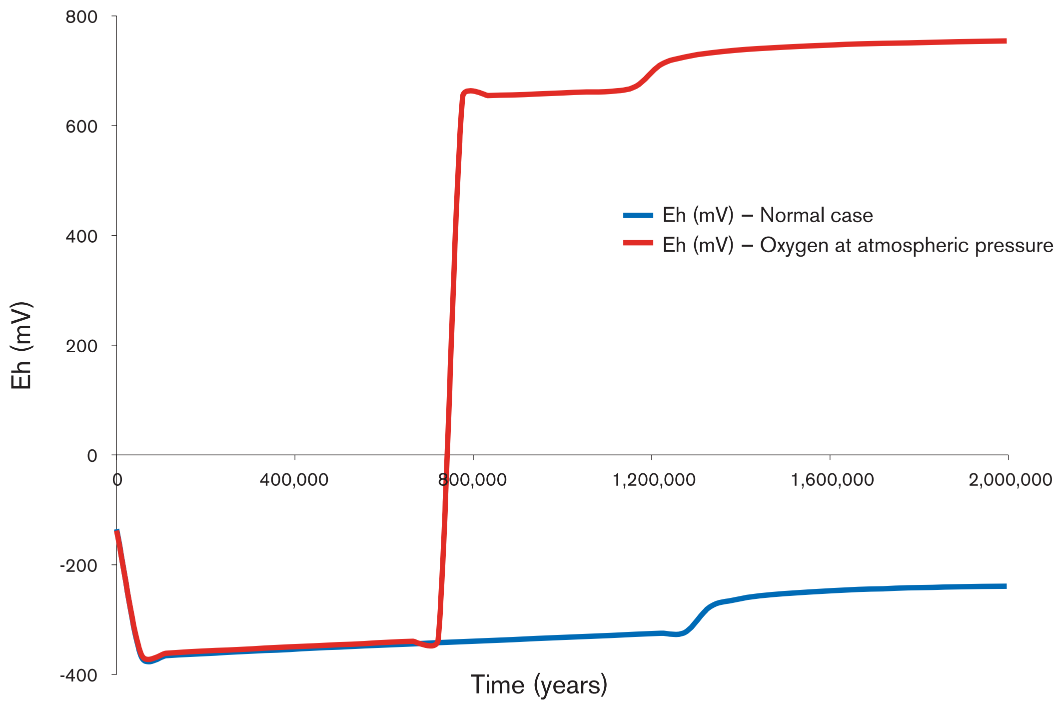

Figure 8-30. *Evolution of redox capacity in contact with Beberg water.*

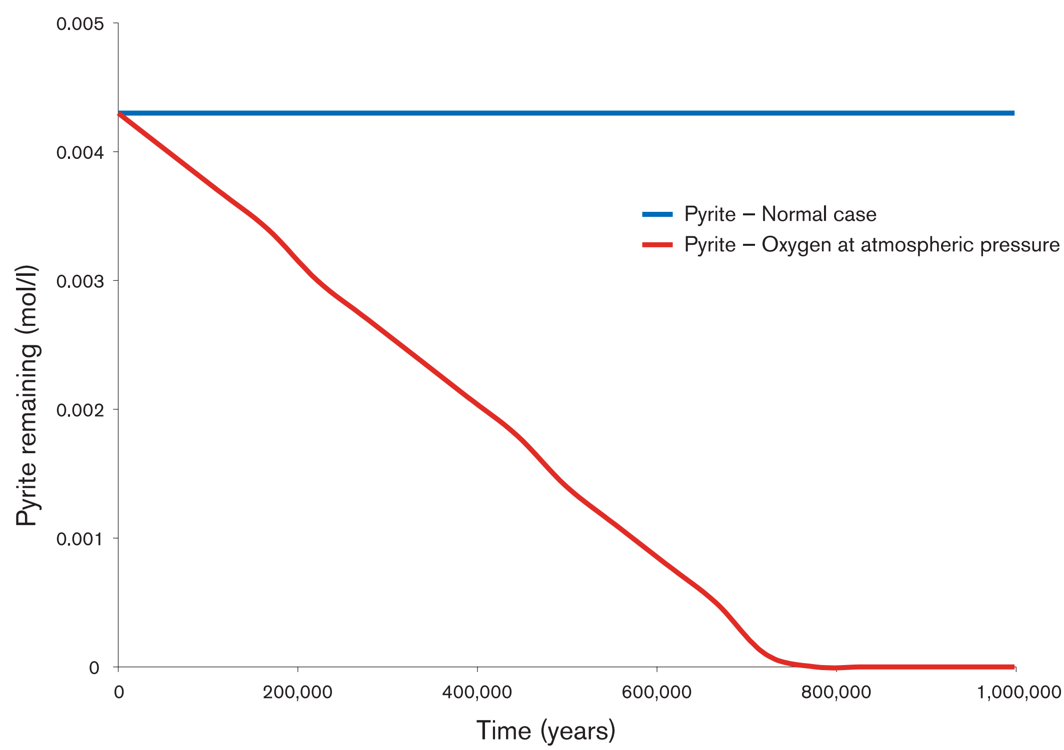

Figure 8-31. *Consumption of pyrite in buffer in contact with Beberg water.*

repository conditions, but the temperature gradient may be of importance here as well. The solubility of the silicon compounds normally increases with increasing temperature, and it is conceivable that silicon could dissolve near the canister, only to precipitate out in the colder part. If this process occurs on a large scale, the precipitated compounds could affect the bentonite's pore system, which could in turn affect the buffer properties.

A modelling of these processes shows that neither calcium sulphate, calcite nor silicon compounds are enriched in the buffer material. The temperature is too low and the gradient too small for precipitations /Arcos, 1999/.

Conversion of montmorillonite to non-swelling minerals

The beneficial physical properties of the buffer, for example swelling capacity and low hydraulic conductivity, are controlled by the interaction between water and montmorillonite in the bentonite. The montmorillonite's mineralogical properties are therefore decisive for the function of the buffer in a deep repository. The mineral is stable in its natural environment, but alterations can be expected under special chemical conditions. The processes lead to a decrease in the montmorillonite content, and it is important to be able to quantify the alteration over long time spans.

In natural systems, elevated temperature and availability of potassium lead to transformation of montmorillonite in the direction towards illite. The process can be written as followed (in simplified terms):

$$Montmorillonite + K^{+} + (Al^{3+}) \rightarrow Illite + Si^{4+} + Ca^{2+} / Na^{+}$$

There are a great many publications (see the Process Report) about the illitization process, from which it can be concluded that the process is not important in a deep repository of the KBS-3 type (maximum temperature < 100ºC). The argumentation can be summarized in three points:

1) Temperature-induced transformation is limited by a shortage of potassium.

In order for a transformation to illite to take place, a supply of potassium ions is needed. Since the natural fraction of potassium in the buffer may be kept low, potassium must be transported in from the surroundings. The potassium requirement to completely convert the montmorillonite in the buffer is about five weight-percent, which is equivalent to nearly a tonne of potassium for one deposition hole. Calculations and modellings show that inward transport of potassium is expected to take place very slowly and that this in itself constitutes an effective obstacle to a substantial transformation. Table 8-11 shows an estimation of the transformation based on immediate reaction between montmorillonite and potassium.

Table 8-11. Estimation of the rate of illitization based on the availability of potassium for Aberg, Beberg and Ceberg. The site-specific potassium concentrations are taken from section 8.9.2 (undisturbed state, non-saline water in Beberg), flow rates from the Data Report.

	Median flux ($m^3/m^2 \cdot year$)	Q_{ekv} (litre/ canister · år)	Potassium concentration (mg/l)	Time for complete conversion (years)	Fraction converted after 1 mill. years (%)
Aberg	$1.8 \cdot 10^{-3}$	3	8	40 million	2.5
Beberg	$1 \cdot 10^{-3}$	3	2	160 million	0.6
Ceberg	$3.3 \cdot 10^{-5}$	0.5	2	1 billion	0.1

2) The bentonite material is close to mineralogical equilibrium to start with.

In its original environment, the bentonite is normally close to mineralogical equilibrium, i.e. only insignificant mineralogical changes take place. In a deep repository, the exchange between buffer and surrounding environment is strongly limited, and the mass of the buffer is relatively great. The bentonite in the buffer will therefore create its own chemical environment to start with (see e.g. /Fritz 1984/). Figure 8-32 shows stability ranges for montmorillonite/illite with respect to pH, potassium and silicon content at 25°C. As can be seen, if the silicon concentration is in equilibrium with quartz the montmorillonite is not stable, whereas if the silicon concentration is controlled by amorphous silicic acid it is stable. At low temperatures the precipitation of quartz is very slow and the only mechanism for removing silicon is transport with the groundwater. The flows are much too low, however, and the difference in silicon concentration between buffer and groundwater is so small that the effect is negligible. Two early changes in the chemical environment are obvious, however:

- Increase in the ion content of the pore water as a result of inward transport of solutes during water saturation. For ordinary groundwater, the increase is small in relation to the naturally high cation concentration that exists in the montmorillonite in the buffer.
- Temperature increase as a result of fuel decay. The period with significantly elevated temperature is, however, relatively short; after 1,000 years, for example, the elevation is less than 20°C in Ceberg /Ageskog and Jansson, 1999/.

The system can thus be expected to be close to mineralogical equilibrium during most of the repository period.

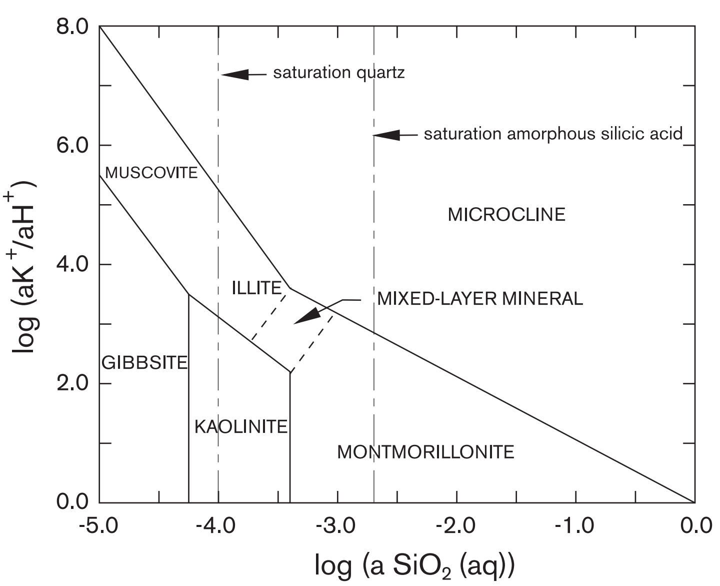

***Figure 8-32**. Stability ranges for montmorillonite/illite with respect to pH, potassium and silicon content at 25°C. Simplified from Agard and Helgesson /1983/.*

3) The transformation rate at the repository's maximum temperature is very low.

Kinetic models exist for smectite-to-illite conversion. Relationships and constants have been established by means of laboratory experiments and comparisons with natural systems, e.g. Eberl and Hower /1976/, Pytte /1982/ and Huang et al /1993/. Huang's model shows a conversion rate of 50 percent after one million years at 90°C and 400 ppm potassium. The conversion rate is considerably lower at expected temperatures and potassium concentrations.

Colloid formation/erosion

Montmorillonite from the expanding buffer is expected to some extent to intrude into fractures around the deposition holes. The groundwater in the fractures could then conceivably erode the buffer. Two possible causes of erosion have been identified:

- Chemical erosion where the clay gel is dispersed.
- Mechanical erosion where clay particles are torn loose by the flowing water.

In order for the clay gel to be chemically stable and not be dispersed to a colloidal suspension, the water must contain a sufficient concentration of positive ions, cations. Calcium is, for example, common in deep groundwaters and if the calcium concentration exceeds 4 mg/l the clay gel is stable. In the reference waters for the three sites (see section 8.9.2) the Ca^{2+} concentrations are high enough to prevent erosion, both today and in the future.

Mechanical erosion requires very high groundwater flow rates. A calculation of the critical rate shows that it exceeds typical mean rates at repository depth by a factor of at least 1,000.

Under the conditions that prevail in the deep repository in the base scenario, the long-range extent of erosion is expected to be negligible. The probability of erosion under extremely ion-poor groundwater conditions needs to be further studied.

Intrusion of water with high ionic strength

The groundwaters at Aberg, Beberg and Ceberg have much too low ionic strengths for this to be of importance for the buffer's swelling capacity. If water with much higher ionic strength should enter the repository, this could affect the properties of the buffer /Process Report/.

Increased ion concentration generally leads to reduced potential swelling, and thereby to similar effects on the pore geometry as an ion exchange to divalent ions /Norrish and Quirk, 1954/. Increased ion concentration also leads to a reduction of the swelling pressure due to osmotic effects, and to changes in the pore geometry that affect the material's hydraulic conductivity /Karnland, 1997/.

The effect of high ion concentration on swelling pressure can be calculated with thermodynamic models. Maximally pessimistic models indicate that the swelling pressure decreases with increasing salinity, disappearing entirely in the buffer at an NaCl content of about 7 percent. Calculations based on less pessimistic assumptions and experimental pre-studies show that swelling pressure can be expected even in saturated salt solutions /Karnland, 1997/. Figure 8-33 shows the results of these calculations.

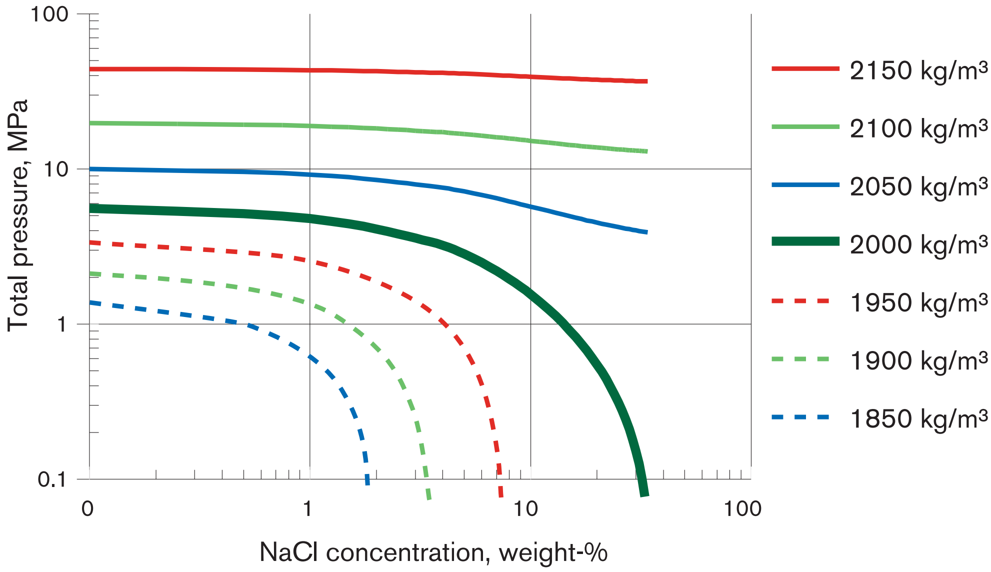

Figure 8-33. *Swelling pressure as a function of salinity for Na-bentonite at different densities.*

Laboratory studies of Canadian bentonite support the latter calculation /Dixon et al, 1996/. Temperature effects on swelling pressure and hydraulic conductivity are not experimentally documented for very high salinities.

Summary

The above account shows that:

- Ion exchange in combination with calcite dissolution affects both pH and the buffer's swelling capacity. The modelling shows that the water's pH will rise by 1–2 units when it comes into contact with the buffer. The ion exchange will convert some of the Na-montmorillonite into Ca-montmorillonite. This affects the swelling capacity. In Aberg, the swelling pressure could decline to approximately 4–5 MPa in around 100,000 years. This does not affect buffer function, however.
- The pyrite in the buffer is expected to consume the oxygen that could enter during repository construction and operation. The water that comes into contact with the canister is therefore always expected to be reducing. When natural (reducing) groundwater is in contact with the buffer, pyrite is stable and does not affect the chemistry.
- Potassium ions in the groundwater, combined with elevated temperature, could transform the montmorillonite to non-expandable minerals (illite). However, the process is too slow to be of any significance.
- Silicon oxides, carbonates (calcite and siderite) and calcium sulphate (anhydrite) have inversely temperature-dependent solubilities and could "migrate" into the buffer during the period with a temperature gradient. The results from the simple model described above show, however, that the temperatures are too low and the gradients too small for this to be of any importance.

The buffer material is selected and apportioned to retain its favourable properties for a very long time. The processes described in this section will affect the properties of the buffer in a long time perspective, but the magnitude of these effects are small enough so that the long-term safety criteria for hydraulic conductivity, density and swelling pressure (section 5.7) are met with good margin.

The differences between the natural groundwaters at Aberg, Beberg and Ceberg do not lead to any decisive differences in the chemical evolution of the buffer. The most important differences are that:

- The Ca/Na ratio in Aberg is higher, so that ion exchange from Na to Ca will be more or less complete after a long time, resulting in reduced swelling pressure.
- The initial pH in Ceberg is so high that the pH after reaction with the buffer is projected to rise to 10.7.

The result of the chemical analyses, namely that the buffer is expected to retain its function for a very long time, is not surprising considering the fact that the buffer material comes from an environment that long resembled the conditions in the Swedish bedrock.

The buffer material in SR 97, bentonite with the trade name MX-80, is taken from the border area between Wyoming and South Dakota. The bentonite was formed 100–120 million years ago by fallout of volcanic ash in the sea that divided the North American continent at that time. The water in the sea was fresh or brackish, i.e. similar to Swedish groundwaters. The bentonite was covered relatively quickly by sediment and then remained under these conditions up to about 60 million years ago, when postglacial land uplift raised the deposits above the groundwater table.

The chemical evolution of the backfill has not been discussed in any great detail. It will be adapted to the selected site to satisfy the safety criteria. This needs to be further examined in future safety assessments.

8.9.4 Corrosion of the copper canister

The copper canister's isolating capacity is a central factor in repository safety. An important task in the safety assessment is therefore to determine how the 5 cm thick copper shell could be damaged chemically, i.e. by different types of corrosion. Stress corrosion cracking is dealt with in the Process Report, where the conclusion is drawn that the process can be neglected. The following section deals with chemical corrosion and is based on Werme /1998/.

Metallic copper is very stable thermodynamically under the oxygen-free conditions that naturally prevail at repository depth. This stability could be disturbed by a substance that forms copper phases which are even more stable than the metallic phase. The only component of this kind that has been identified in deep Swedish groundwaters is **sulphide**. Sulphide has also been identified as the only impurity in the buffer that could potentially cause copper corrosion.

Another cause of corrosion could be chloride ions. Copper forms strong chloride complexes, which could increase the rate of outward transport of dissolved copper. However, high chloride concentrations (<100 g/l) in combination with pH values below 3 are required in order for such a process to be of importance. The bentonite is an effective pH buffer, and the water around the canister is estimated to have a pH between 7 and 11.

During the early post-closure period, corrosion could also be caused by **oxygen** from the construction and operation of the repository and by **nitric acid** formed by γ radiolysis of nitrogen compounds in humid air in the canister-buffer gap.

Oxygen corrosion

Residual oxygen in buffer and groundwater from repository construction and operation can be shown with simple, pessimistic assumptions to lead to a maximum corrosion depth of around 0.03 millimetre evenly distributed over the canister surface. This is assuming that all oxygen admitted during construction and operation has led to copper corrosion. Pitting (local corrosion attacks) has also been analyzed for these conditions. The maximum pitting depth has been pessimistically estimated to be a couple of millimetres, but will probably be much less.

Corrosion by nitric acid

Corrosion caused by nitric acid formed by radiolysis in the canister-buffer gap can also be shown to be negligible with simple approximations. It is assumed in these calculations as well that all nitric acid that can theoretically form is consumed in copper corrosion.

Sulphide corrosion

The reaction

$$2Cu(metal) + 2H_2O \leftrightarrow 2Cu^+ + H_2 + 2OH^-$$

leads at equilibrium to a free copper ion concentration of around 10^{-20} M. Hydrogen sulphide that comes into contact with the canister can form copper sulphide according to:

$$2Cu^+ + HS^- \rightarrow Cu_2S + H^+$$

where the equilibrium concentration of copper ions is approximately 10^{-25} M. If copper sulphide precipitates, more copper ions will be liberated from the canister. The net reaction for sulphide corrosion will be:

$$2Cu + HS^- + H_2O \rightarrow Cu_2S + OH^- + H_2$$

Sulphide is present in the groundwater and in the buffer's pore water. Furthermore, sulphide-containing minerals, mainly pyrite, can dissolve and contribute sulphide in both buffer and rock.

Sulphide from buffer: The pyrite content of the buffer, about 0.3 percent, can be converted to sulphide in the pore water under oxygen-free conditions. If all pyrite in the buffer in a deposition hole is consumed in copper corrosion, this is equivalent to a corrosion depth of approximately 0.5 mm, assuming an evenly distributed attack over the surface. The pyrite is evenly distributed in the buffer, and there is no reason to expect local attacks. The process is estimated to take about 300,000 years. The potential sulphide content of the buffer thus gives a negligible reduction of the canister's wall thickness.

Sulphide in the groundwater: The rate of corrosion caused by sulphide in the groundwater is controlled by the rate at which the sulphide can be transported to the canister. Both the slow groundwater flow and the buffer's transport resistance limit the corrosion rate.

In order to estimate the rate if only the buffer is limiting, it can be assumed that the groundwater flow is able to transport dissolved sulphide to the buffer's boundary with the rock in sufficient quantity in order to sustain the natural concentration in the groundwater there. The corrosion rate, $R_{Corr/Buffer}$, can then be estimated with:

$$R_{Corr/Buffer} = \frac{2C_{Sulphide}\, D_e M_{Cu}}{d_{Buffer}\rho_{Cu}}$$

where $C_{Sulphide}$ is the sulphide concentration in the groundwater, d_{Buffer} is the thickness of the buffer (0.35 m), D_e is the diffusivity of sulphide in the buffer (assumed to be $3 \cdot 10^{-4}$ m^2/y), and M_{Cu} and r_{Cu} are the molar weight and density of copper, respectively. It has then been assumed that all sulphide that penetrates the buffer immediately reacts with copper.

If instead only the groundwater flow's transport capacity around the deposition hole limits the rate, the corrosion rate can be estimated with:

$$R_{Corr/Flow} = \frac{2C_{Sulphide}\, \phi\, M_{Cu}}{\rho_{Cu}}$$

where ϕ is the groundwater flow around the deposition hole.

Table 8-12 shows the results of both estimations for Aberg, Beberg and Ceberg.

In the least favourable case, where only a pessimistically high flow rate limits the corrosion in Aberg, the canister's estimated life is around 10 million years. The buffer resistance alone gives a theoretical life of 500 million years in Aberg.

Thus, the groundwater flow and the buffer each independently limit the corrosion rate so that canister life can be theoretically calculated to be at least 10 million years. It is also worth noting that the buffer is not necessary to guarantee canister life in this respect.

Table 8-12. Estimation of the rate of copper corrosion limited by either the buffer's transport resistance or the groundwater flow for Aberg, Beberg and Ceberg. The site-specific sulphide concentrations in the reference waters are taken from section 8.9.2, median and pessimistic flow rates from the Data Report.

	Sulphide concentration $C_{Sulphide}$ mg/litre	Corrosion rate $R_{Corr / Buffer}$ cm/year	Groundwater flow ϕ $m^3/(m^2 \cdot year)$		Corrosion rate $R_{Corr / Flow}$ cm/year	
			Median	Pessimistic	Median	Pessimistic
Aberg	0.14	10^{-8}	0.002	0.1	10^{-8}	$6 \cdot 10^{-7}$
Beberg	< 0.01	$< 4 \cdot 10^{-10}$	0.001	0.02	$< 4 \cdot 10^{-10}$	$< 8 \cdot 10^{-9}$
Ceberg	< 0.01	$< 2 \cdot 10^{-10}$	$4 \cdot 10^{-5}$	$2 \cdot 10^{-4}$	$< 9 \cdot 10^{-14}$	$< 4 \cdot 10^{-13}$

Sulphate reduction

The above calculations are based on measured concentrations of sulphide minerals in the buffer and concentrations of sulphide in the groundwater. Sulphate-reducing bacteria could produce more sulphide from the sulphate content of the buffer and groundwater.

The sulphide concentrations in Swedish groundwaters are, however, generally limited by the fact that sulphide is precipitated as solid minerals, mainly by reaction with iron, when the sulphide concentrations become high enough. The highest sulphide concentrations measured in Swedish groundwaters lie around 1 mg/l, see section 8.9.2. This means that bacterial sulphate reduction in the rock is of limited importance; the sulphide concentration cannot reach unacceptable levels anyway.

It has further been shown that sulphate-reducing bacteria cannot survive in highly compacted bentonite.

Pitting

Canister life could be shortened if corrosion was very local. But there is no known mechanism for sulphide corrosion that could lead to local corrosion attack.

It can nevertheless be expected that corrosion will not take place evenly over the canister surface, but the deepest corrosion is probably not more than twice as deep as the mean value.

8.9.5 Confidence; evolution of groundwater composition

Process understanding

The understanding of the fundamental reactions as well as the mechanisms of solute transport with the groundwater is good, see the Process Report.

Models

Models that deal with groundwater composition and evolution in different ways are not used directly for predictions in the safety assessment. The model set is constantly being developed and helps improve the understanding of the hydrogeochemical evolution on a repository site.

Data

Data uncertainty is generally great. In the first place, the present-day situation can only be observed at isolated points (boreholes) in the heterogeneous geosphere, and in the second place, the future evolution will be controlled by conditions outside the repository area and by residual effects of the historic climatic evolution, both of which are associated with great uncertainties. In recognition of these uncertainties, the future groundwater composition on a repository site must be specified as a range of values. Confidence that such ranges can be determined by systematically taking into account factors and uncertainties that influence the values is good.

8.9.6 Confidence; chemical evolution of the buffer

Process understanding

The fundamental understanding of all processes involved in the chemical evolution of the buffer is sufficient for satisfactory treatment in the safety assessment. The longterm effects of erosion under extreme conditions may need to be further investigated.

Models and data

Confidence in the models and data used for calculations of the chemical evolution of the buffer is deemed to be sufficient for the relatively rough model calculations required in the base scenario.

8.9.7 Confidence; canister corrosion

Process understanding

The fundamental understanding of different mechanisms of copper corrosion in the deep repository environment is good, see the Process Report.

Models and data

In the safety assessment, quantitative estimations of copper corrosion are performed by means of rough calculations, which provide sufficient accuracy. Data uncertainties are above all associated with the availability of corrodants. The uncertainties are handled pessimistically in the safety assessment.

8.9.8 Conclusions

No long-range changes have been identified in the base scenario that contradict the conclusion that the groundwater at repository depth will remain oxygen-free in a million-year perspective.

The long-range composition of the groundwater in general, and its content of substances that could harm the canister or buffer in particular, can be estimated site-specifically by the use of ranges. The size of the range is determined by uncertainties in the presentday site-specific groundwater composition and in the longterm evolution of the flow situation and the hydrochemical conditions in the bedrock.

The range can be used to study the chemical evolution in buffer and canister, for example by pessimistically assuming that the most unfavourable value in the range will prevail. Such analyses show that the buffer is expected to retain a sufficiently high swelling pressure, a sufficiently high density and a sufficiently low hydraulic conductivity on all sites in a very long time perspective. The canister is projected to withstand the corrosion attacks to which it will be subjected in a million-year perspective with good margin.

The treatment of the long-range function of the backfill material needs to be refined for future safety assessments. The extent of erosion under extremely ion-poor groundwater conditions may also need to be studied further.

8.10 Summary

8.10.1 The base scenario in a time perspective

As an introduction to the summary of the results of the analysis of the base scenario, the entire time sequence is summarized here, divided into three epochs.

The initial 100 years

The radiotoxicity of the fuel declines during this epoch to approximately 60 percent of its radiotoxicity at deposition.

Immediately after deposition, a heating of the entire repository begins, driven by the decay heat in the fuel. The maximum temperature on the outside of the canister, 90ºC, is reached after about 10 years. The temperature maximum at the boundary of the deposition holes is reached after about 20 years. On a larger scale, the temperature maximum at repository depth is reached after 90 years in Beberg (45ºC) and after 80 years in Ceberg (40ºC).

The buffer, which initially has a degree of saturation of about 80 percent, absorbs water from the surrounding rock as it heats. The time to full water saturation is some ten years and varies with the hydraulic conditions in the rock around the deposition hole. At the same time, the groundwater level above the repository is gradually restored.

In the final phase of the buffer's water saturation sequence, a swelling pressure is developed against the canister. The swelling pressure and the groundwater pressure together exert a total pressure of around 12 MPa against the canister, which is far below the mechanical load the canister can withstand. The swelling pressure may be unevenly distributed over the canister surface, especially during the water saturation phase. The mechanical stresses to which this gives rise in the canister are also far below the stresses the canister is designed to take. The thermal expansion of the host rock can cause millimetre-sized fracture movements around the deposition holes.

The hydrogeochemical evolution during the initial 100 years is characterized by a perturbation of the natural situation due to the fact that water in the region around the repository has been drawn in towards the repository as a consequence of the constant pumping-out of the groundwater during construction. Deeper lying saline water can in this way be drawn up to the vicinity of the repository. The chemical conditions are also disturbed by the oxygen and engineering and stray materials brought into the repository during construction. Both organic and inorganic materials are expected to be consumed so that the groundwater composition approaches the original composition within 100 years.

One hundred to 10,000 years

The radiotoxicity of the fuel decreases during this epoch from 60 percent to approximately 0.6 percent of its radiotoxicity at deposition. The heating of the geosphere continues, and a heat wave is projected to reach the surface, although its impact will be negligible. In the case of a two-level repository in Aberg, the temperature maximum between the repository levels (55ºC) will be reached after about 450 years.

Hydraulically only small changes occur during this epoch. The buffer is saturated with water and the groundwater's flow in the geosphere is similar to the natural situation that prevailed before repository construction. With time, land uplift will affect the flow, especially on the island of Aberg, which is expected to become a part of the mainland in about 2,000 years, but the effects on the flow will be small.

The mechanical situation for buffer and canister is expected to be steady-state, since the buffer remains water-saturated. The heating of the geosphere leads to a build-up of stresses that are partially relaxed by thermal expansion. Certain fractures close and others open, but the effect is probably not great enough to cause fracturing. In major fracture zones, centimetre-sized thermally-induced movements may occur.

In the long term, changes in the flow conditions cause the saline water at Aberg and the mixture of non-saline and saline water at Beberg to change to a composition that increasingly resembles today's non-saline water at Ceberg.

In the buffer, the buffer's original content of sodium ions is exchanged for calcium ions in the groundwater. Calcite in the buffer is slowly dissolved.

The buffer has such a low hydraulic conductivity that transport of solutes, including canister corrodants, takes place entirely by diffusion. Corrosion processes in the copper shell have negligible consequences during this epoch.

The time after 10,000 years

In reality, major climate changes are likely during this epoch. The course of events under present-day climatic conditions is studied in the base scenario to be used as a basis for comparison to judge the effects of climate changes that are uncertain in both type and scope.

In 100,000 years, radiotoxicity declines to about 0.05 percent of its initial level and then remains on a par with that of uranium ore mined to produce the fuel. There are still small amounts of radionuclides in the fuel that can move relatively easily through the repository's barriers if the canister should be damaged, and larger quantities of less mobile nuclides. The decay heat after 10,000 years has declined to less than one percent of its original value, and the temperature conditions in the repository system once again approach the natural situation.

Since today's climate persists according to the scenario definition, the hydraulic situation in the geosphere remains unchanged. The groundwater composition around the repository also remains unchanged.

During this epoch, the mechanical load on the repository rock is affected by slow, large-scale movements in the bedrock as well as by the rock's own long-range material properties, which can cause time-delayed deformations (creep movements). Rough calculations show that the effects of both these processes are negligible.

The chemical evolution of the buffer is characterized by continued ion exchange and dissolution of calcite. In Aberg, a complete exchange from sodium to calcium is expected after several hundred thousand years. The effect will be a reduction of the swelling pressure to 4–5 MPa. At Beberg the process is about 10 times slower, and at Ceberg the transformation is never complete since the sodium/calcium ratio in the groundwater is too high. The reduction in swelling pressure is of no importance for the function of the buffer. Nor does the calcite dissolution or the influence of the surrounding groundwater cause any changes that affect the buffer's normal function.

8.10.2 Overall conclusions

The canister retains its isolating function during the evolution of the repository system.

The mechanical stresses on the canister from groundwater pressure, buffer swelling pressure and rock movements around the deposition holes are all far below what is needed to jeopardize canister isolation. The mechanical evolution in the host rock has been discussed in a hundred thousand year perspective, and there is no reason to doubt that a million year perspective would result in the same assessment.

Nor do the chemical stresses on the canister in the form of corrosion by oxygen or sulphide cause damage to the copper shell that would jeopardize isolation, not even on a timescale of a million years.

The assessment is based, among other things, on the requirements that the canister's surface temperature should be less than 100ºC and that the water at repository depth should be oxygen-free. The former can always be achieved by a suitable deployment of the deposition holes or by adjusting the fuel content of the canisters. Oxygen has never been observed in deep Swedish groundwaters. Oxygen in rainwater is as a rule consumed effectively before it leaves the soil layer. Furthermore, there are microbes in the rock and minerals in both rock and buffer with a very great potential for oxygen consumption. In the base scenario, no long-term changes or processes have been identified which contradict the conclusion that the groundwater at repository depth will be oxygen-free in a million year perspective.

The assessment of canister integrity is also based on the requirement that the buffer should function as intended, which among other things means that the buffer should have a sufficiently low hydraulic conductivity, a sufficiently high density and a sufficient swelling pressure. Processes such as ion exchange, mineral alterations or erosion do not cause in the base scenario any changes in the properties of the buffer that could jeopardize canister function in even a million year perspective. The result is as expected, considering the fact that the buffer material is taken from a natural environment where conditions have for millions of years resembled conditions at repository depth in Swedish bedrock.

8.10.3 Coming work

The analysis of the base scenario can be done more rigorously as sitespecific data on the geosphere on an actual repository site become available. Other parts of the underlying material and the analysis of the scenario can also be refined in some respects mentioned in the text. Possible improvements include:

- Calculations of canister strength with realistic, inhomogeneous material properties for various situations.
- Site-specific rock-mechanical analyses.
- Analysis of variants where the buffer is assumed to be defective or improperly deposited.
- A more detailed analysis of the evolution of the backfill.
- Study of the probability of buffer erosion under extremely ionpoor groundwater conditions.
- Analysis of the early hydromechanical evolution of the canister-buffer gap.

The presentation can be refined in pedagogical terms as well, for example with more figures that illustrate for different subsidiary evolutions which processes are dealt with by model calculations, which are neglected, etc. It should also be possible to show using standardized graphs how most of the variables in the system description change with time. In this way it is possible to depict in a uniform manner, as a series of time-dependent curves, such variables as the fuel's aggregate radiotoxicity and decay heat, the temperature on the canister surface, the median flow at repository depth, the water content of the buffer, the swelling pressure in the buffer, the Ca content of the buffer, etc. Such an illustration would augment the presentation in e.g. section 8.10.1.

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