Technical Report

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What requirements does the KBS-3 repository make on the host rock?

Geoscientific suitability indicators and criteria for siting and site evaluation

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April 2000

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Foreword

This report gives an account of what requirements are made by the deep repository on the rock and what requirements can be used for siting and evaluation of sites in conjunction with site investigations. The work was initiated in 1997 and an interim report was submitted in conjunction with RD&D-Programme 98 /SKB, 1998/. The work is an important part of SKB's preparations for execution of the site investigations. The report conveys SKB's standpoint in these matters, based on the facts presented.

The project has been carried out during a period of just under three years by a group consisting of Karl-Erik Almén, Christer Svemar, Lars O Ericsson, Johan Andersson and the undersigned. A reference group with the following composition was also connected to the project:

- Kaj Ahlbom, Siting, SKB
- Karin Andersson, Technical Environmental Planning, Chalmers University of Technology
- Stefan Claesson, Isotope Laboratory, Swedish Museum of Natural History
- Allan Hedin, Safety Assessment, SKB
- Pär Olsson, Skanska

The reference group has provided valuable contributions to the final report.

It should also be mentioned that experts within the disciplines of geology, rock mechanics, geohydrology, chemistry, thermal properties and transport properties of the rock have gathered on a number of occasions during the course of the work to augment the knowledge bank on which this report ultimately rests.

Anders Ström
Project Manager
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Summary

This report gives an account of what requirements are made on the rock, what conditions in the rock are advantageous (preferences) and how the fulfilment of requirements and preferences (criteria) is to be judged prior to the selection of sites for a site investigation and during a site investigation. The conclusions and results of the report are based on the knowledge and experience acquired by SKB over many years of research and development. The knowledge gained during SKB's most recent safety assessment, SR 97, is particularly drawn on. The reported requirements, preferences and criteria will be used in SKB's continued work with site selection and site investigations.

The results, and particularly the stipulated criteria, apply to a repository for spent fuel of the KBS-3 type, i.e. a repository where the fuel is contained in copper canisters embedded in bentonite clay at a depth of 400–700 m in the Swedish crystalline basement. If the repository concept is changed or if new technical/scientific advances are made, certain requirements, preferences or criteria may need to be adjusted. Therefore, it should be emphasized that the work cannot be used as a basis for siting of other types of repositories or in other geological settings.

The formulations of requirements are governed by Swedish laws and regulations. To achieve a safe final repository, SKB has developed a final repository concept (KBS-3) based on the fundamental safety functions of isolation and retardation. These functions are influenced by the design and construction of the facility and the engineered barriers, and by the site-specific conditions on the repository site. A number of general requirements and preferences can also be formulated for facility construction.

The report analyzes how the rock's different geological conditions, mechanical properties, thermal properties, hydrogeological properties, chemical properties and transport properties influence the functions of the deep repository, and whether it is possible to determine requirements and preferences regarding the influence of these properties. Where possible, these requirements or preferences have then been translated into requirements or preferences regarding the individual properties (parameters). Parameters that can be used to determine whether requirements or preferences are satisfied are called geoscientific suitability indicators. In order to be able to determine at different stages during a site investigation whether requirements and preferences for a given parameter are satisfied, criteria are formulated that are based on the quantities that can be measured or estimated at the relevant stage of the investigation.

Generally, terms such as siting factor and criteria are often used without any precise definition. The following definitions apply in this study:

Term	Definition
Function	Purpose which the deep repository is intended to serve, for example to have an isolating and retarding function.
Parameter	Physical or chemical quantity (property, condition in the rock).
Requirement	Condition that must be satisfied, refers to actual conditions regardless of siting stage. All requirements must be satisfied.
Preference	Condition that ought to be satisfied regardless of siting stage. All preferences do not have to be satisfied, however.
Geoscientific suitability indicators	Measurable or estimable site-specific parameters that can be used in a given siting stage to assess whether requirements and preferences are satisfied.
Criteria for evaluation	Values for suitability indicators in a given siting stage that are decisive for the site assessment of whether a site satisfies stipulated requirements and preferences.

What requirements do we make on the rock?

Numerous conditions need to be determined in a site investigation in order to build up a fundamental understanding of the site. But only certain conditions are of direct importance for whether the site is suitable for a repository or the layout of the repository on the investigated site.

The following requirements are made on the rock or the placement of the deep repository in the rock:

- The rock in the repository's deposition zone may not have any ore potential, i.e. may not contain such valuable minerals that it might justify mining at hundreds of metres' depth.
- Regional plastic shear zones shall be avoided if it cannot be demonstrated that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be so-called "tectonic lenses" near regional plastic shear zones where the bedrock is homogeneous and relatively unaffected.
- It must be possible to position the repository with respect to the fracture zones on the site. Deposition tunnels and deposition holes for canisters may not pass through or be positioned too close to major regional and major local fracture zones. Deposition holes may not intersect identified local minor fracture zones.
- The rock's strength, fracture geometry and initial stresses may not be such that large stability problems may arise around tunnels or deposition holes within the deposition area. This is checked by means of a mechanical analysis, where the input values comprise the geometry of the tunnels, the strength and deformation properties of the intact rock, the geometry of the fracture system and the initial rock stresses.
- The groundwater at repository level may not contain dissolved oxygen. Absence of oxygen is indicated by a negative Eh, occurrence of Fe(II), or occurrence of sulphide.
- The total salinity (TDS = Total Dissolved Solids) in the groundwater must be less than 100 g/l at repository level.

In addition to the above requirements, there are a large number of preferences, i.e. conditions that are desirable and should be taken into account when positioning the repository in the rock:

- Since it can be difficult to predict how different rocks and minerals will be used in the future, it is preferable to site the deep repository in commonly occurring rock types.
- Moderate density (fracture surface area per volume) of local minor fracture zones is preferable, along with moderate density of fractures.
- It is generally an advantage if the initial rock stresses at the planned repository depth do not deviate from what is normal in Swedish crystalline bedrock.
- It is preferable that the strength and deformation properties of the intact rock be normal for Swedish bedrock, since experience has shown it is possible to carry out rock works with good results in such bedrock.
- It is preferable that the coefficient of thermal expansion have normal values for Swedish bedrock (i.e. within the range 10^{-6} to 10^{-5} K^{-1}) and that it not differ markedly between the rock types in the repository area.
- The rock should have a higher thermal conductivity than 2.5 W/(m,K). Areas with a high potential for geothermal energy extraction should be avoided. The undisturbed temperature at repository depth should be less than 25°C.
- It is an advantage if a large part of the rock mass in the deposition zone has a hydraulic conductivity (K) that is less than 10^{-8} m/s.
- Fracture zones that need to be passed during construction should have such low permeability that they can be passed without problems, which means the zones should have a transmissivity (T) that is lower than 10^{-5} m^2/s and are furthermore not problematical from a construction-related viewpoint.
- It is an advantage if the local hydraulic gradient is lower than 1% at repository level, but lower values do not provide any additional advantage.
- Undisturbed groundwater at repository level should have a pH in the range 6–10, a low concentration of organic compounds ([DOC]<20mg/l), low colloid concentration (lower than 0.5 mg/l), low ammonium concentrations, some content of calcium and magnesium ($[Ca^{2+}]+[Mg^{2+}]>4$ mg/l) and low concentrations of radon and radium.
- It is preferable that it be possible to find canister positions in a large fraction of the rock that have a Darcy velocity lower than 0.01 m/y on a canister hole scale, since lower fluxes increase the retardation of important radionuclides.
- It is preferable that a substantial retardation of important radionuclides take place in the geosphere. A quantitative preference can be expressed in the form of the transport resistance (F parameter), where Darcy velocity, flow distribution and the flow-wetted surface area per volume of rock (or equivalent parameter) are such that a large fraction of all flow paths have F greater than 10^4 y/m.
- It is desirable that matrix diffusivity and matrix porosity not be much lower (by a factor of 100 or more) than the value ranges analyzed in the safety assessment SR 97. The accessible diffusion depth should at least exceed a centimetre or so.
- Areas where biological diversity or species worth protecting may be threatened and areas which are or may be important water sources, soil sources or farmland should be avoided for the deep repository's surface facilities. (Areas protected by law are avoided.)

As a general rule, satisfied preferences lead to greater safety margins, lower costs, simpler investigations or simpler construction of the repository. All preferences do not have to be satisfied for a site to be approved for a deep repository. It may very well be so that "poorer" values for certain parameters are compensated for by "better" values for others. An integrated safety assessment and a construction analysis are therefore always needed to assess safety and performance.

In addition to the above preferences that have directly to do with the properties of the rock, there are preferences that facilitate the characterization of the site. In particular:

- It is preferable that there be a high proportion of exposed rock and otherwise moderate soil depth (preferably less than about 10 m), since this facilitates determination of the lithological and geological-structural conditions in the underlying bedrock from the ground surface.
- It is preferable that the bedrock be homogeneous with few rock types and regular fracturing, although a small-scale variation in mineral composition, such as in a gneiss, is no disadvantage.

Even though the requirements and preferences have been formulated on the basis of different safety and construction viewpoints, there is scarcely any example of a conflict between different requirements or preferences. As a rule, conditions that lead to good long-term safety are also advantageous from the construction viewpoint.

Selection of areas for site investigations

Requirements and preferences regarding the rock should of course be used as far as possible to formulate criteria for selection of sites for site investigations. Good knowledge of the conditions on the ground surface usually exists after completion of a feasibility study, while knowledge of conditions in the deep rock is very limited. Criteria can therefore normally only be formulated for the following suitability indicators:

- After completion of a feasibility study, continued studies and investigations are only conducted of areas that are not deemed to have a potential for occurrence of ore or valuable industrial minerals and that are deemed to be homogeneous and to consist of commonly occurring rock types.
- During the feasibility study, the study site is selected and adapted so that a deep repository can be positioned with good margin in relation to regional plastic shear zones and the regional fracture zones interpreted in the feasibility study.
- Areas protected by law are avoided, and areas for further investigations are chosen so that they have few conflicting interests (for example a water source) and so that the surface portion can be adapted with little impact on the near-surface ecosystem.
- Areas with an unsuitably high topographical gradient on a regional scale (greater than 1%) are rejected.

The feasibility studies thus identify areas with a good potential to have suitable conditions. But site investigations (from boreholes) are necessary to check this. At the same time, the report's survey of the generic knowledge of the Swedish crystalline bedrock shows that good prospects should exist to find sites in Sweden that satisfy all requirements and most of the essential preferences.

Under what circumstances should the site investigation be discontinued?

An overall safety assessment and an overall construction analysis comprise essential background material in an integrated assessment of whether a site is suitable. The site is only accepted if it is possible to show in the safety assessment that a safe deep repository can be constructed. During a site investigation, when measurement data have been obtained from repository depth but before the overall assessment has been carried out, criteria are used to check whether the above requirements and preferences may be satisfied. The criteria provide guidance on the outcome of the assessments and can therefore also be used to review a safety assessment.

The following criteria are so important that the site investigation should be discontinued and another site chosen if they cannot be met:

- If large deposits of ore-bearing minerals or valuable industrial minerals are encountered within the repository area, the site should be abandoned.
- During the site investigation, the repository is adapted more precisely to the then-identified fracture zones. Suitable respect distances to major identified regional and local major fracture zones can only be determined site-specifically, but it is assumed that a distance of at least several tens of metres to major local zones and at least 100 metres to regional zones is appropriate. If the repository cannot be positioned in a reasonable manner (if it would have to be split up into a very large number of parts) in relation to regional plastic shear zones, regional fracture zones or local major fracture zones, the site is not suitable for a deep repository.
- If the repository cannot be reasonably configured in such a way that extensive and general stability problems can be avoided, the site is unsuitable and should be abandoned. Extensive problems with “core discing” of drill cores should give rise directly to suspicions that such problems may arise.
- At least one of the indicators negative Eh values, occurrence of Fe^{2+} or occurrence of sulphide must be fulfilled by the results of the measurements of groundwater composition at repository depth. If none of the indicators can clearly indicate the absence of dissolved oxygen, a more thorough chemical assessment is required. If not even these further studies can indicate oxygen-free conditions, the site must be abandoned.
- Measured total salinities (TDS = Total Dissolved Solids) at repository level must be lower than 100 g/l. Occasional higher values can be accepted if it can be shown that the water is located in areas that can be avoided and that the water will not be able to flow to the repository area.

Besides these direct disqualifying criteria, the suitability of the site can be questioned if a large fraction of the rock mass between fracture zones has a hydraulic conductivity greater than 10^{-8} m/s. High permeability of the rock requires local precision adaptation of the repository if the safety margins are to be met.

Contents

1 Introduction

This report gives and account of what requirements and preferences are made by the deep repository on the rock and what criteria should be used for evaluation of sites in conjunction with site investigations. The work was initiated in 1997. An interim report was submitted in conjunction with RD&D-Programme 98 /SKB, 1998/.

1.1 Purpose

When SKB's programme for final disposal of spent nuclear fuel moves into the site investigation phase, it is necessary to define exactly which measurable properties in the rock may be of importance for long-term safety and which may be of importance for being able to build the repository on the investigated site in a rational manner. The information is needed to provide guidance on the selection of sites, to provide guidance on what is to be measured in the site investigation, and to be able to evaluate the site during the ongoing investigation in a structured manner.

Laws and ordinances require that the deep repository be safe. To check that the requirement is met, SKB carries out a safety assessment. The assessment deals with a large number of processes in the repository and in the rock that influence the repository's performance and evolution with time. The repository site could also be affected by many different events and circumstances. This makes it difficult to specify detailed requirements on the different properties of the rock and on initial conditions on the repository site. The requirements, preferences and criteria that can be made on the rock can therefore only provide guidance. They do not take the place of overall and complete safety assessments.

The question of siting of the deep repository is currently being considered in many countries. The progress report /Ström et al., 1998/ provides a brief description of the situation in a number of countries with a special emphasis on to what extent requirements and criteria have been formulated for the rock. General international recommendations exist, such as the IAEA's document "Siting of deep geological repositories" /IAEA, 1994/. The present report provides guidance in the siting of a deep repository for spent nuclear fuel of the KBS-3 type in the Swedish crystalline bedrock. The work cannot be used directly as a basis for siting of other types of repositories or in other geological settings.

1.2 Goal

The goal of the project has been to answer, as clearly as possible, the following questions:

- What requirements are made on the rock for it to be suitable for a deep repository for spent nuclear fuel of the KBS-3 type, and what conditions in the rock render it unsuitable for a repository?
- What conditions in the rock are advantageous for such a deep repository?

The answers to these questions have a great influence on the continued siting work. They clarify the geoscientific goals of feasibility studies and site investigations and they influence how the site investigation programme should be structured.

The more detailed goals of the project have been to:

- identify and quantify requirements and preferences regarding the rock's properties and conditions from the perspectives of long-term safety and engineering feasibility,
- propose criteria that can be used both to assess the fulfilment of requirements and preferences and, if possible, to compare sites after feasibility studies and during the site investigations.

1.3 Background

The schematic design of a deep repository for spent nuclear fuel proposed by SKB, KBS-3, has been analyzed and developed over a period of more than 20 years. The feasibility of disposing of nuclear waste in the Swedish crystalline bedrock have been analyzed over an even longer period of time. The suitability of the method has been demonstrated in a number of safety assessments such as KBS-3 /KBS, 1983/ and most recently in SR 97 /SKB, 1999a/. Long experience exists in Sweden of rock cavern construction in crystalline bedrock from mines and engineering projects. Great efforts have been devoted over a long time to geoscientific characterization of the properties and structural composition of the bedrock.

The interim goal of being able to choose at least two sites for site investigations in 2001 is set in SKB's RD&D-Programme 98 /SKB, 1998/. The work of developing geoscientific suitability indicators comprises a part of the extensive background material SKB needs to commence and successfully carry out the site investigations. The need for suitability indicators has also been expressed for several years by the regulatory authorities and the Swedish Government in their reviews of and findings on SKB's RD&D programmes.

General siting factors have been described previously by SKB, for example in conjunction with the supplement to RD&D-Programme 92 /SKB, 1994/. These factors were then accepted by the Government and the regulatory authorities "*...as a suitable point of departure for the continued work*". At the same time, SKB considered it necessary in preparation for the site investigations to define "factors and criteria" more precisely. In General Siting Study 95 /SKB, 1995b/, SKB described conditions on a national scale as a general background to the fundamental prospects for siting of a deep repository. An extensive project was carried out in 1996 to identify all the parameters that can be determined in a geoscientific site investigation. The results were published in a separate report /Andersson et al., 1998a/.

The Government's decision of 19 December 1996 in response to SKB's RD&D-Programme 95 /SKB, 1995a/ states that General Siting Study 95 /SKB, 1995b/ should be supplemented. A progress report /Ström et al., 1998/ on the project was published in conjunction with the presentation of RD&D-Programme 98 /SKB, 1998/ which, together with a separate analysis of questions relating to a coastal/inland siting and comparisons between northern and southern Sweden /Leijon, 1998/, constituted the supplement called for by the Government.

The Government's decision of 24 January 2000 in response to SKB's RD&D-Programme 98 /SKB, 1998/ stipulates a number of conditions for the continued research and development programme. According to these conditions, SKB shall *"Present an overall evaluation of completed feasibility studies and other material for selection of sites for site investigations"*.

SKI's statement of comment on RD&D-Programme 98 /SKI, 1999/ states the following: *"SKI is however in full agreement with SKB that the suitability of a site for a repository must ultimately be judged on the basis of an integrated safety and design analysis that takes into account uncertainties and the interaction between different factors. The criteria fulfil an important function in clarifying what characterises a suitable site for a repository. However, on their own, the criteria do not provide an adequate basis for judging whether the site complies with the basic safety criteria."*

SKI also stresses the coupling between the work of developing siting factors and the work with the safety assessment SR 97:

"On the basis of an up-to-date safety assessment (SR 97), SKB must also reconcile and clearly account for the minimum criteria and discriminating factors which determine whether a site can be judged to be suitable for a repository."

"SR 97, *in addition to demonstrating safety assessment methodology, should also provide a basis for...specifying the factors on which the selection of sites for site investigation will be based; deriving the parameters which must be determined and the other criteria which should be made with respect to a site investigation..."*.

These requests from SKI are satisfied by the fact that the work in this project is to a high degree based on the results and insights achieved in SR 97. This is also evident from the different references on which the report is based.

1.4 Context and related work

In response to the Government's decision on RD&D-Programme 98, statements from the Swedish Nuclear Power Inspectorate and viewpoints from the feasibility study municipalities, SKB intends to submit a supplementary account in accordance with the conditions in the Government's decision. The account is planned to be contained in a report, the RD&D-98 supplement, with the sections "Method selection", "Selection of investigation sites", "Programme for site investigations" and "Consultation". The present report comprises a portion of the supporting material for the RD&D-98 supplement. Examples of other supporting material are SR 97, the site investigation and evaluation programme and compilation of feasibility studies, and other siting material with choice of sites. Figure 1-1 provides an overview of the scope of the supporting material.

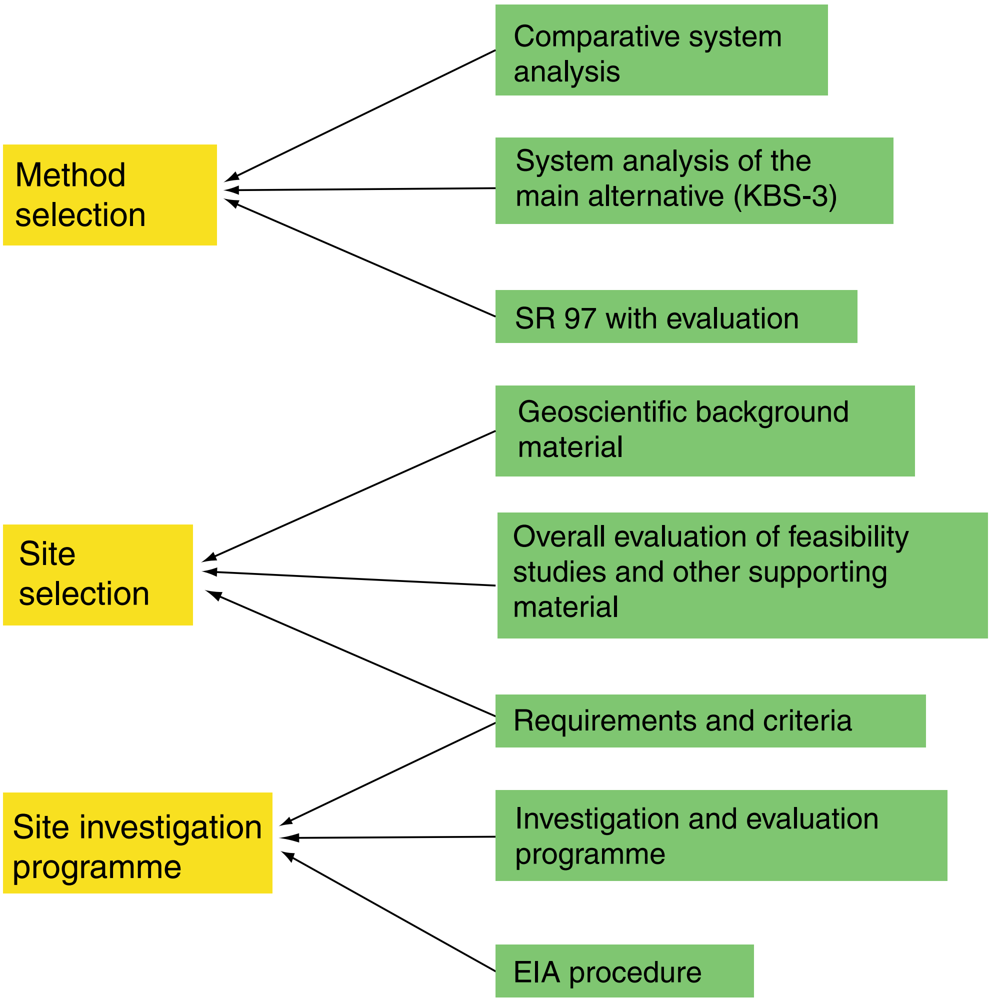

Figure 1-1. *Overview of SKB's overall account in preparation for the site investigation phase, i.e. the supplement to RD&D-98. The work with requirements and criteria comprises one of the main references.*

1.4.1 Safety assessment SR 97

A central point of departure for the project work has been the SR 97 safety assessment published by SKB in December 1999. Several of the goals of SR 97 have a direct bearing on the work with requirements, preferences and criteria. These goals are:

- SR 97 shall provide supporting material 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.
- SR 97 shall provide supporting material for specifying the factors that serve as a basis for the selection of areas for site investigation and deriving what parameters need to be determined and what other requirements should be made on a site investigation.
- SR 97 shall provide supporting material for deriving preliminary functional requirements on the canister and the other barriers.

The fundamental structure of a safety assessment and how it can be used to define suitability indicators is discussed in section 2.2. This report is based to a high degree on the results of analyses carried out within SR 97.

SR 97 consists of a separate Main Report /SKB, 1999a/ and three sub-reports (the "Repository System Report") /SKB, 1999c/, the "Process Report" /SKB, 1999b/ and the "Data Report" /Andersson, 1999/. Both the main report and the sub-reports are based in turn on results reported in a large number of other reports.

1.4.2 Overall programme for investigation and evaluation of sites

The preparatory work for the site investigations also includes developing a distinct site investigation programme. By "site investigation programme" is meant here an overall programme for investigation and evaluation of sites with respect to long-term safety and technology. The programme should thus detail what information is intended to be collected from a site and how it is to be used in evaluation of a site. This is where the present report enters into the picture. The evaluation programme will demonstrate the use of requirements, preferences, indicators and criteria during ongoing site investigations. Figure 1-2 provides and overview of these related activities and how they are linked to each other.

The overall programme will be supplemented and detailed in discipline-specific programmes. These are also generic, i.e. not tailored to the specific conditions that exist on a particular site. When areas for site investigations have been selected, the discipline-specific programmes will be reworked into site-specific execution programmes. These will take into account the site-specific geological conditions, as well as land and environmental interests and societal circumstances.

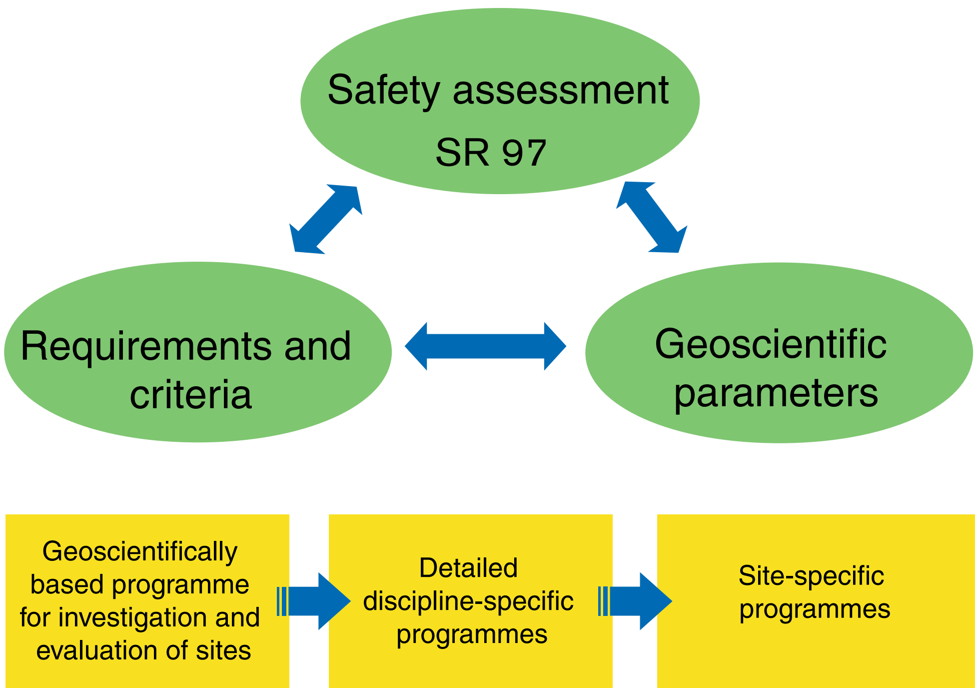

Figure 1-2. *Outline of site investigations and an overview of related activities and how they are linked to each other.*

1.5 This report

Chapters 1–3 describe premises and employed methodology. The actual account of the work is found in Chapters 4–9. The conclusions of the work are presented in Chapter 10.

Chapter 2 describes what fundamental requirements a deep repository must satisfy. Requirements and preferences that are presented in this chapter comprise the basis of the work of formulating more detailed requirements and preferences regarding the rock.

Chapter 3 gives an account of the premises for the work. This includes definitions of the terms function, parameter, requirement, preference, suitability indicator and criterion. During the project work it has proved necessary to use a strict vocabulary and structure in reports. The procedure for developing criteria proceeds in steps, and it should be possible to understand how a concrete requirement or preference regarding a given property of the rock is derived from one of the more fundamental requirements which the deep repository must satisfy.

Chapters 4 to 9 present requirements and preferences regarding the function of the deep repository, requirements and preferences regarding the properties of the rock (parameters), expected value ranges for these parameters, and proposals (with reasons given) for criteria to be used during and after a feasibility study, as well as during and after the site investigations. Chapter 4 deals with geology, Chapter 5 rock mechanics, Chapter 6 temperature properties, Chapter 7 hydrogeology, Chapter 8 groundwater composition (chemistry), and Chapter 9 the transport properties of the rock. The contents of these chapters are also summarized in tables in Appendices A and B.

2 General requirements and preferences

There are fundamental requirements which a deep repository must satisfy. These requirements are defined by laws and regulations issued by the regulatory authorities. The safety of the deep repository is based on the safety functions isolation and retardation. These functions are affected both by the design and construction of the facility and engineered barriers, and by the site-specific conditions on the repository site. A safety assessment is carried out in order to evaluate safety. A number of general requirements and preferences can also be formulated for the actual construction work. They serve as a basis for the work of formulating detailed requirements and preferences regarding the rock.

2.1 Laws, ordinances and regulations

The general requirements on the deep repository emanate from the acts of law passed by the Swedish Parliament. The most important laws in this regard are the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act. Permits under both the Environmental Code and the Nuclear Activities Act are required to build a deep repository.

2.1.1 Environmental Code

The Environmental Code regulates, among other things, the issuance of permits for siting of the deep repository and the preparation of environmental impact statements. The code further regulates what environmental impact the deep repository can be permitted to have.

2.1.2 Nuclear Activities Act and Radiation Protection Act

Requirements on safety and radiation protection are set forth in the Nuclear Activities Act and the Radiation Protection Act. The Nuclear Activities Act prescribes in general that nuclear activities shall be conducted in a safe manner. The Radiation Protection Act prescribes in general that anyone conducting activities with radiation shall, depending on the nature of the activities and the conditions under which they are conducted, adopt whatever measures and precautions are needed to prevent or counteract harm to humans, animals and the environment. The ordinances issued by the Government pursuant to the Nuclear Activities Act and the Radiation Protection Act contain some more detailed provisions and regulate the activities of the Swedish Nuclear Power Inspectorate (SKI) and of the Swedish Radiation Protection Institute (SSI). The ordinances are still couched in very general terms regarding requirements on safety and radiation protection in the deep repository.

2.1.3 Regulations and draft regulations

In addition to the laws mentioned above, SKI and SSI are empowered to issue regulations.

The National Radiation Protection Institute (SSI) recently issued regulations concerning final disposal of spent nuclear fuel /SSI, 1998/. Some provisions of these regulations have a bearing on the work with siting factors and criteria. The final disposal of spent nuclear fuel shall be radiologically optimized and based on the best available technology. A final repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk after closure is no more than 10^{-6} for the individual exposed to the greatest risk. Furthermore, final disposal shall be carried out in such a manner that biological diversity is preserved and a sustainable utilization of biological resources is protected against the harmful effects of radiation.

The Swedish Nuclear Power Inspectorate (SKI) has sent out draft regulations governing safety in the final disposal of spent nuclear fuel etc. It is stated there that safety, in both the short and long term, shall be based on a system of passive natural barriers and that a deficiency that might arise in one of the barriers should not impair the safety of the final repository. It is further stated in the proposal that features, events and processes that are of importance for the post-closure safety of a final repository should be analyzed before the repository is built, before it is commissioned and before it is closed.

The question of whether the fundamental requirements are met for a deep repository on a specific site will be considered in conjunction with the regulatory review of the safety assessments and environmental impact statements which SKB is obligated to submit. It should also be observed that regulations do not directly stipulate requirements on the performance of different parts of the deep disposal system, but discuss in more general terms requirements on the system as a whole. In other words, laws and regulations cannot be used directly to formulate requirements or preferences on the properties of the rock. Such requirements or preferences can only be derived indirectly, based on the impact they may have on the safety of the repository.

When it comes to the actual construction of the deep repository, the National Board of Occupational Safety and Health stipulates specific requirements on the rock works (AFS 1997:3) and on the blasting works (AFS 1994:17). These provisions must be taken into account in planning the construction of the deep repository and thereby also impact the site investigations.

2.2 What makes the deep repository safe?

2.2.1 Safety principles

The safety principles for a deep repository are presented in SR 97. A deep repository shall primarily 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 by a system of barriers, see Figure 2-1:

- 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 rock movements and prevents groundwater from flowing around the canister, which prevents corrosive substances from entering the canister. The bentonite clay also effectively adsorbs radionuclides that are released if the canisters should be damaged.

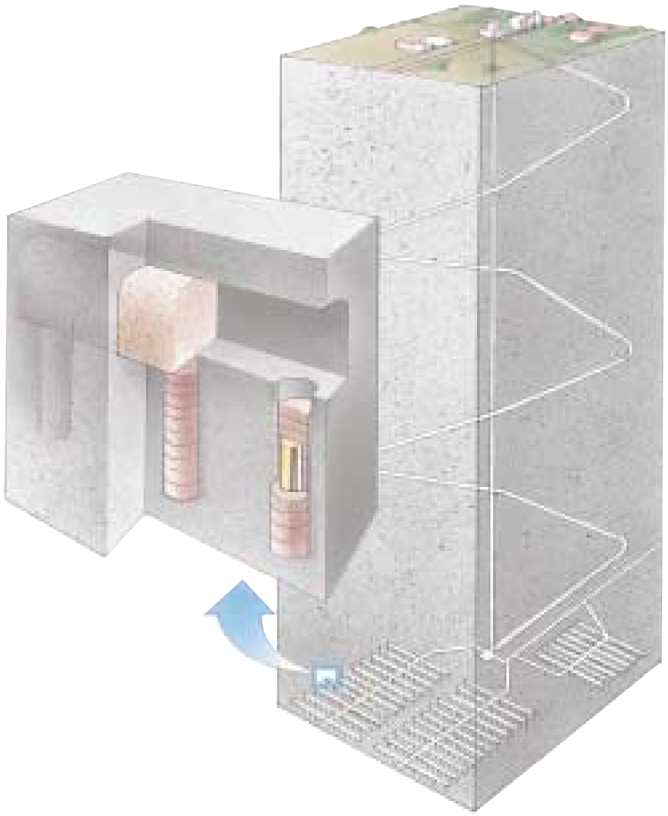

Figure 2-1. The KBS-3 system with the main alternative that the canisters are deposited one by one in vertical holes. Variants with several canisters per hole or with horizontal holes may also be considered. The conclusions of the report are also applicable to these variants.

- 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.
- If any canister should be damaged, the chemical properties of the fuel and the radioactive substances, 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.

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.

The main alternative for the KBS-3 method is that the canisters are deposited one by one in vertical holes from the deposition tunnels (Figure 2.1). The variants that may be considered are:

- vertical deposition of two canisters in each hole,
- horizontal deposition of several canisters per hole.

The results and conclusions of this report are also applicable to these variants.

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 is supposed to contribute to the isolation function by keeping the canister in place and preventing corrosive substances from coming into contact with the canister.

The rock also contributes to this isolation 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. It is advantageous if the water contains low concentrations of substances that could be harmful to the copper canister and the bentonite. It is also advantageous if the water flows 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.

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. This release is limited by the fact that many of the radionuclides with the highest long-term toxicity 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. The clay buffer should have a capacity to retain many of the radionuclides with the highest long-term toxicity by adherence to the surfaces of the clay particles. The rock is supposed to contribute to this retardation by virtue of the fact that radionuclides adhere to the surfaces of the fractures and/or penetrate into microfractures containing stationary water so that they have a much longer travel time than the groundwater itself. Besides the actual design of the deep repository, it is primarily the composition (chemistry) of the groundwater, the groundwater flow in the rock (hydrogeology) and the transport properties of the rock that influence the repository's retarding function.

Dilution and dispersal

Dilution and dispersal have also previously also 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 the safety assessment SR 97 /SKB, 1999/ 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.

2.2.2 Safety assessment

A safety assessment is carried out in order to evaluate long-term safety. The purpose, contents and outline of a safety assessment are described in detail in SR 97. In brief, the safety assessment can be said to consist of:

- a thorough description of the appearance or state of the repository system when it has just been built,
- a survey of what changes the repository can be expected to undergo with time as a consequence of both internal processes and external forces, and
- an evaluation of the consequences of the changes for long-term safety.

This approach is common in the analysis 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 interaction with the changing surroundings.

Just as important as the assessment of the repository's isolating capacity and the numerical result of the analysis of retardation is confidence in the results. The data underlying a safety assessment are always associated with deficiencies of various kinds. To put it simply, we are faced with the task of showing that the repository has been designed with sufficient margins to be safe in spite of the incomplete knowledge available. Confidence in the results is dependent on how methodically the uncertainties/deficiencies have been handled.

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

System description: First a structured description is performed of all internal processes, their interrelationships and the properties of the repository that are influenced by a particular process. This task also includes defining the boundary between a system and its surroundings.

Initial state: The initial state of the repository, i.e. what it looks like when it has just been completed, is then described (dimensions and materials in the engineered portions of the repository and structure and properties of the geosphere around the repository).

Choice of scenarios: The evolution of the repository is influenced by its surroundings. 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.

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 discussions and simple approximations to detailed modelling based on site-specific data. For the scenarios where a canister is damaged, calculations are made of radionuclide transport from the damaged canister through the different barriers, and what dose this release could give rise to. The calculations are performed with a chain of transport models (COMP23, FARF31, BIO42), which in turn obtain input data from various more or less complex model calculations or data analyses of different conditions or phenomena, see Figure 2-2.

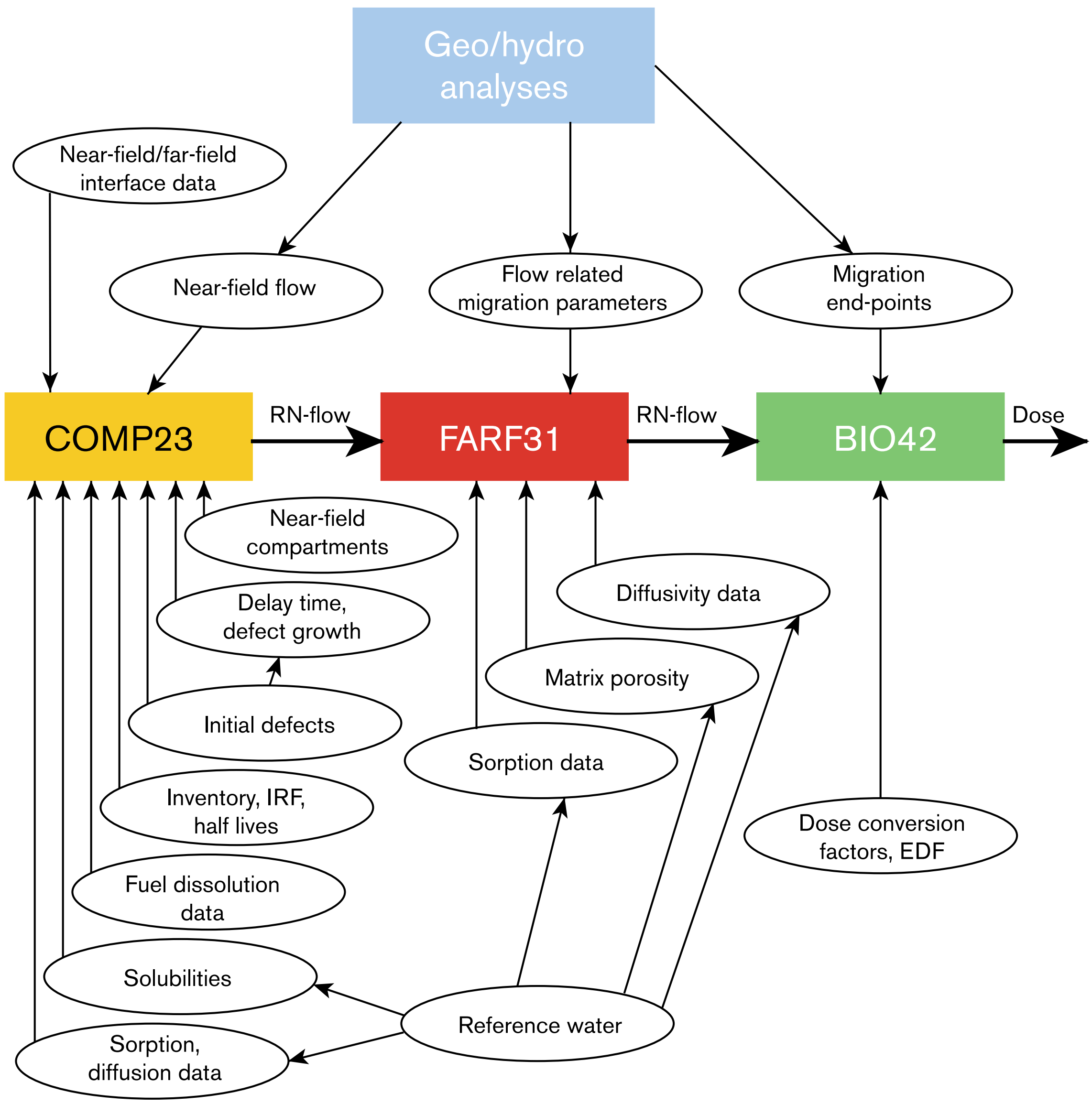

Figure 2-2. *Models used in SR 97 for calculation of radionuclide transport (rectangles) and input data for these models (ellipses).*

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.

2.2.3 How the safety assessment can be used to formulate requirements and preferences regarding the rock

The work of developing geoscientific suitability indicators and criteria is based on many years of experience, analyses and development of the KBS-3 method. The safety assessment SR 97 has comprised an essential complement to the data used in the project. The assessments of what is essential from the viewpoint of long-term safety are based on the analyses performed within the framework of SR 97, complemented with previous knowledge and experience.

- For each site-related parameter needed to describe the safety assessment's initial state (see above), the question has been asked whether this parameter should be a geoscientific suitability indicator.
- The safety assessment has been used to seek an answer to the question of whether that are value ranges where the deep repository's isolation can be threatened. As a precaution, such value ranges have comprised a basis for formulating requirements, even though it is not always clear that the deep repository would definitely be unsafe if the requirements were not met. The requirements can only be reconsidered in the light of new knowledge or if the design of the repository is significantly altered.
- The safety assessment has also been used to find grounds for preferences regarding value ranges that contribute to good isolation or good retardation. Such value ranges result in desired function, but do not necessarily define the borderline to unacceptable function. Such a borderline is in many cases influenced by other parameters, is relative, is unknown or can be influenced by repository layout.

The requirements define conditions that may not occur. The preferences define conditions that lead to good isolation and retardation, but the deep repository may very well turn out to be safe even if many preferences are not satisfied. The requirements and preferences have been formulated to provide guidance in the siting work and to be able to prioritize investigation activities in site investigations. They do not take the place of integrated and complete safety assessments. (Chapter 3 provides stricter definitions of the terms function, parameter, requirement, preference, suitability indicator and criterion.)

2.3 Fundamental civil engineering aspects

Requirements and preferences that are framed from the rock engineering perspective are of a somewhat different character than the direct safety requirements. The repository layout is designed primarily to achieve as good performance and safety as possible: canister and tunnel spacings are determined by requirements on temperature in and around the repository, major discontinuities are avoided, etc. Furthermore, pure rock excavation aspects such as water seepage and rock stability in tunnels will be taken into account. The general rule is that conditions that are favourable from a safety viewpoint also entail good constructability and a safe working environment. Good constructability and a stable rock facility are further advantageous for safety during the operation of the facility. There is therefore seldom any conflict between the requirements and preferences that can be formulated from different viewpoints.

The general requirements from a civil engineering perspective can be summarized in the following points:

- the working environment shall be safe,
- the environmental impact of investigations, of construction and of operation shall be limited and kept within acceptable levels,
- construction shall only have a limited and transient impact on the safety functions of the deep repository,
- excavation of deposition areas shall be able to take place at the same time as deposition in other areas.

Beyond this there are preferences that

- the rock work can be done with as few interruptions and as little use of extraordinary reinforcement and sealing measures as possible (good constructability),
- the deposition area does not have to be split up into a very large number of subareas, and that it is possible to position deposition tunnels in a flexible manner in the selected deposition areas.

During and after site investigations, a construction analysis is carried out for the chosen repository layout where constructability, time and material consumption, environmental impact, working environment, etc. for the rock construction are analyzed. If the safety assessment or construction analysis indicates unreasonable consequences or costs for the chosen layout, the latter needs to be changed. In other words, the construction analysis does not impose any absolute requirements, since adjustments can generally be made to suit prevailing conditions. There are, on the other hand, a number of factors that influence constructability and costs.

2.4 Other general requirements and preferences

As noted earlier, the work reported here is restricted to the properties of the rock and the soil. This means that such aspects as transportation, land use, management of natural resources and societal factors are not dealt with in the present report.

Prior to the selection of sites for site investigations and the selection of a site for detailed characterization, all conditions that can influence the choice need to be considered, not just the geoscientific conditions. All geoscientific requirements must of course be satisfied. Prior to the selection of a site for detailed characterization, a safety assessment must show that a safe deep repository can be built there. However, many geoscientific preferences are such that, if they are satisfied, this entails lower costs or a shorter investigation time. In site selection, such preferences must be weighed against other environmental and societal preferences. SKB will explain how this weighing-together should be done in another context. Ongoing and upcoming EIA consultations deal with these matters and will clarify these other aspects.

3 Premises, terms and methods

The project work has departed from a number of premises and has proceeded stepwise. Certain fundamental terms are defined in this chapter, after which the methodology used in the work is described.

3.1 Premises

The following premises apply to the work:

- The project is limited to the formulation of requirements, preferences, suitability indicators and criteria.
- Requirements and preferences pertain to a repository for spent nuclear fuel of the KBS-3 type, i.e. a repository where the fuel is contained in copper canisters embedded in bentonite clay at a depth of 400–700 m in the Swedish crystalline basement (see section 2.2). (It should however be noted that the conditions that are suitable or less suitable for a KBS-3 repository with variants can also be assumed to be suitable or less suitable, respectively, for other designs of a deep repository in crystalline bedrock. More specific requirements and preferences, as well as the relative importance of different factors, can, however, change if other repository designs are studied.)
- The work has been limited to discussing the properties of the rock and the soil. This delimitation entails that matters pertaining to e.g. transportation, land use and management of natural resources, or societal factors, are not dealt with other than cursorily. (These matters are dealt with in other parts of SKB's siting studies.)

Precise definition of criteria is limited to the stages prior to site investigation and during and after completed site investigation. In certain cases, however, a theoretical discussion of criteria is held that only becomes meaningful during the detailed characterization or the deposition phases.

3.2 Definitions

A vital point of departure for this project is to differentiate between the requirements and preferences that can be made on the rock, what different measurements can be performed to try to determine the properties of the rock, and what decisions can be made when the measurement results have been analyzed. Concepts such as "siting factor" and "criteria" are often used without defining the term. It also seems as if the words have been used in slightly different senses in different contexts. Stricter definitions of a number of terms are therefore used in this study (see also Table 3-1):

By the *function* of a deep repository is meant the purposes which the deep repository is intended to serve, for example to have an isolating and retarding function. Example of function: the canister should isolate the waste from the surroundings, the rock should retard any escaping radionuclides. By *performance* is meant how well this function is served.

By *parameter* is meant a physical or chemical quantity (property, condition, state, variable, feature) of relevance to the deep repository. A parameter can assume different values. Example: orientation of water-bearing structures, flow porosity, pH.

By *requirement* is meant a condition that must be satisfied. Requirements may relate to either functions or individual parameters. Requirements define the limits of what is not acceptable on a site. Example: the requirement that groundwater at repository level may not contain dissolved oxygen can be established based on the fundamental safety function that the integrity of the canister (isolation) may not be threatened.

Preferences refer to conditions that ought to be satisfied. Preferences may relate to either functions or individual parameters. Preferences define what is good, but not necessary. Example: the preference that the rock should have high thermal conductivity can be established based on the construction design preference of fitting as many canisters as possible within a given deposition area.

By *geoscientific suitability indicators* is meant parameters that describe the properties and states of the rock and the groundwater for which there exist site-specific values or assessment grounds and which can be used at one or more stages of the siting work to determine to what extent requirements and preferences are satisfied. Example: the occurrence of Fe^{2+}, indicating oxygen-free conditions.

By *criteria* for site evaluation is meant indicative values of suitability indicators which can, in a given stage, be used to determine whether a site satisfies stipulated requirements and preferences. Criteria are linked to the level of knowledge and therefore change from one siting stage to another. Example: measured occurrence of Fe^{2+} for quality-approved water samples during site investigation could be used as a criterion for verifying the requirement that the groundwater must not contain dissolved oxygen at repository depth.

Requirements and preferences pertain to actual conditions and they remain the same during different stages of the siting work. What can change requirements and preferences are changed premises, a new repository concept or significant new knowledge. All requirements must be satisfied.

Satisfying preferences generally leads to greater safety margins, lower costs, simpler investigations or a simpler design of the repository. All preferences do not have to be satisfied in order for a site to be approved for a deep repository. It is very possible that “poorer” values for certain parameters are compensated for by “better” values for others. An integrated safety assessment and construction analysis are therefore always needed to assess safety and performance. Preferences, as they are formulated in this report, merely provide guidance, but cannot take the place of the safety assessment.

The term “geoscientific suitability indicator” is used in this study instead of the term “siting factor”, which has often been used previously in discussions of siting of the deep repository. The reason for this is partly that the term “siting factor” has been used in several senses, but above all that the term “suitability indicator” corresponds more closely to what is usually used in other environmental contexts. The standard ISO 14 031, which has to do with environmental management and environmental performance evaluation, defines “environmental condition indicator” as a “specific expression that provides information about the local, national or global condition of the environment”, i.e. a descriptive term. Addition of the words “geoscientific” and “suitability” clarifies the fact that the indicators are intended to describe which of the features of the rock are of importance for judging whether the rock is suitable from the viewpoint of long-term safety and engineering. The word “indicator” also clarifies the fact that the project is not about weighting factors.

The distinction between requirements/preferences and criteria is necessary, since geo-scientific investigations never provide complete knowledge of the state and properties of the rock and the groundwater. When assessing site-specific data, it is therefore necessary to evaluate the precision of the parameter estimate against stipulated requirements and preferences. A suitability indicator, and thereby a criterion as well, is based on something that can be measured or estimated. Figure 3-1 illustrates the hierarchy for requirements, preferences and criteria which has been the point of departure for the work of formulating suitability indicators and criteria for them.

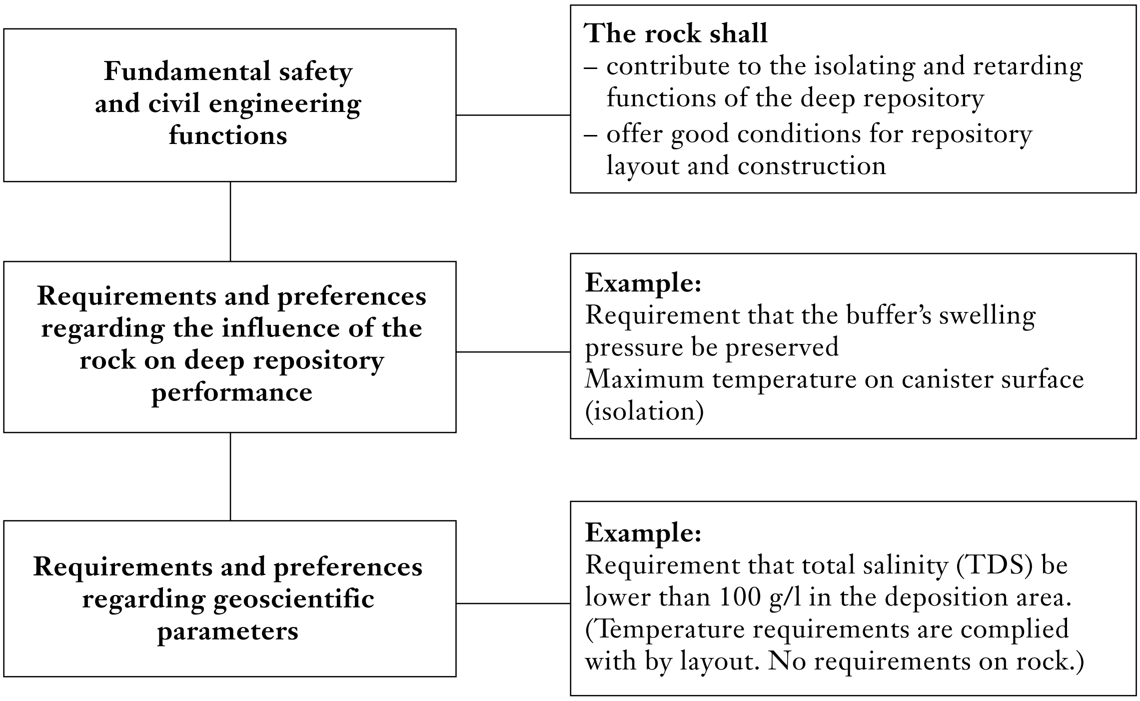

Figure 3-1. *Illustration of the requirement hierarchy that has been the point of departure for the work. Requirements on (the site and) the rock that must be satisfied for the deep repository to be considered safe for disposal (pertains to actual conditions, regardless of siting, construction or operating stage). Not all requirements on function lead to requirements on the rock.*

Table 3-1. Brief definitions of central terms.

Term	Definition
Function	Purpose which the deep repository is intended to serve, for example to have an isolating and retarding function.
Parameter	Physical or chemical quantity (property, condition in the rock).
Requirement	Condition that must be satisfied, refers to actual conditions regardless of siting stage. All requirements must be satisfied.
Preference	Condition that ought to be satisfied regardless of siting stage. All preferences do not have to be satisfied, however.
Geoscientific suitability indicators	Measurable or estimable site-specific parameters that can be used in a given siting stage to assess whether requirements and preferences are satisfied.
Criteria for evaluation	Values for suitability indicators in a given siting stage that are decisive for the site assessment of whether a site satisfies stipulated requirements and preferences.

3.3 Influence on the function of the deep repository

The requirements and preferences that can be made on the deep repository mainly have to do with which functions must or ought to be satisfied. An analysis of the function includes a number of geoscientific parameters, which are schematically illustrated in Figure 3-2, and in some cases the requirements on a given function can, after analysis, be broken down into requirements on individual parameters. In many cases, however, it is difficult to carry out this breakdown, since the function is dependent upon the interacting conditions for many parameters. A certain function can be achieved by many different combinations of parameter values.

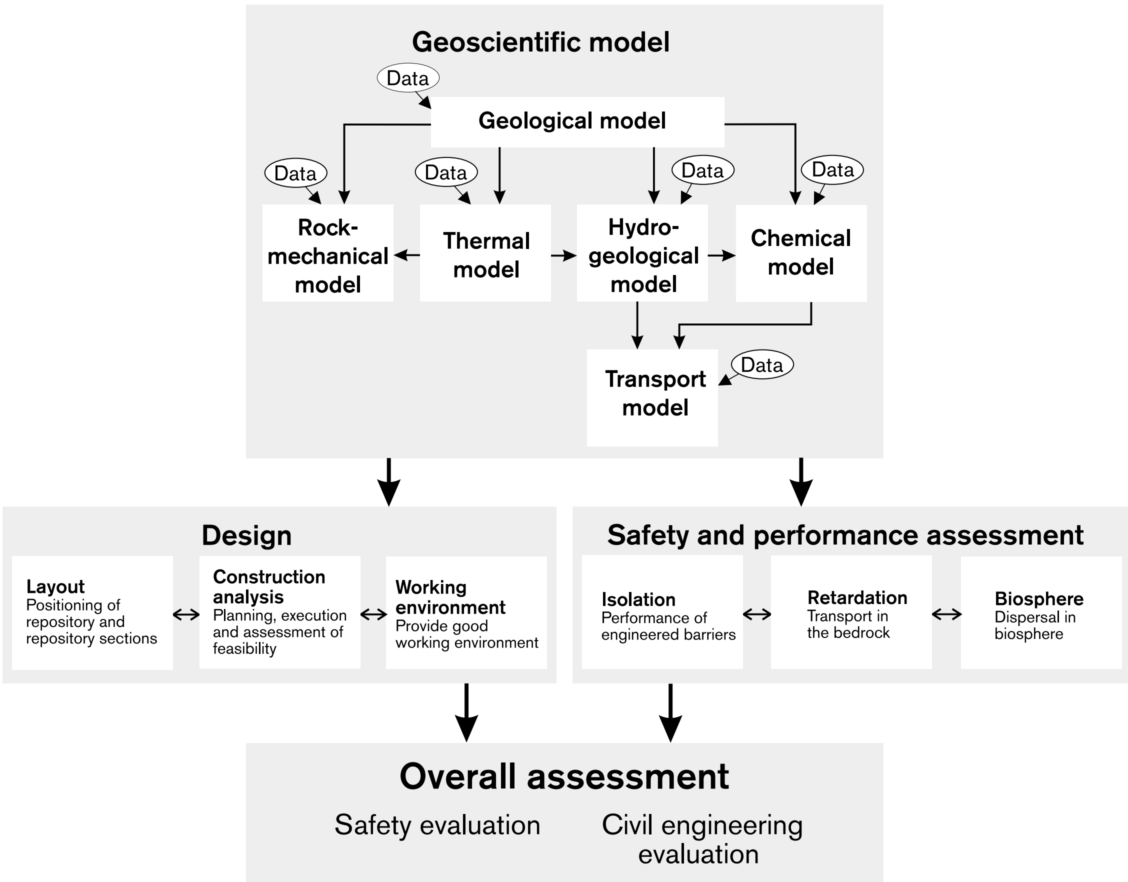

Figure 3-2. *Illustration of how geoscientific models are utilized for design and for safety and performance assessment. Data on the properties of the rock (parameters) serve as a basis for geoscientific models of the bedrock and thereby for assessment of repository performance.*

3.3.1 Breakdown to functions within different disciplines

The general requirements and preferences regarding the performance of the deep repository that were described in Chapter 2 have been broken down and particularized. The question is asked, each in turn, whether geological conditions, rock-mechanical properties, thermal properties, hydrogeological properties, groundwater composition or the transport properties of the rock influence the various functions of the deep repository. If the influence is significant, requirements or preferences are formulated on how great this influence may be. Furthermore, function analyses are identified that can be used during the ongoing site evaluation to check requirements and preferences. The concerned geoscientific parameters are also specified.

3.3.2 Presentation and tables

Requirements and preferences from a functional perspective have been arranged by geoscientific discipline. The structuring has been carried out with the aid of tables divided into the disciplines geology, thermal properties, hydrogeology, rock mechanics, chemistry and transport properties. A table whose rows correspond to the general requirements on safety functions has been set up for each discipline. Table 3-2 shows an excerpt from such a table. The tables are shown in their entirety in Appendix A. The contents of the tables are also presented as the first section in each of the Chapters 4–9.

Each table is divided into the following columns:

- concerned function,
- specific conditions that influence function,
- requirements,
- preferences,
- function analysis and concerned parameters, and
- references.

The purpose of these columns is discussed in the following.

Table 3-2. Example of the structure that has been devised for presentation of requirements and preferences regarding the influence of the rock on the function of the deep repository. The example is taken from the discipline "temperature" and the fundamental safety function pertaining to the isolating function of the canister. The complete function table is shown in Appendix A.

Concerned function	Thermal conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on integrity of canister and buffer	Temperature on canister surface influences chemical environment and thereby canister function.	Requirement on maximum temperature on canister surface T< 100 C.		Layout is determined so that the temperature requirement is met. The temperature the near-field is determined by layout, thermal conductivity, heat capacity, boundary conditions, bentonite saturation.	Werme, 1998. SR 97 Base scenario

Concerned function

The general requirements and preferences regarding the function of the deep repository that have served as a point of departure for the formulation of more detailed requirements and preferences (see Chapter 2).

Specific conditions that influence function

The discipline-specific conditions of importance, i.e. the ones that can influence function, are given for each general safety function.

Requirements

Discipline-specific requirements are given where possible. In principle, only prohibitive requirements are noted here, i.e. if the requirement is not satisfied, this means that the site for the deep repository is unsuitable or that the repository layout has to be decisively modified. Moreover, the safety function is not automatically satisfied even if all requirements are met. The requirements should indicate limits for what is not acceptable.

Preferences

Discipline-specific preferences are given where possible. The preferences should provide guidance on what is needed in order for a safety assessment or a construction analysis to indicate satisfactory conditions. The preferences may thereby relate to e.g. known value ranges for satisfactory conditions, but do not have to define the exact limit for unacceptable function, since such a limit is in many cases relative, unknown or can be influenced by modification of the repository layout.

In preparation for a decision to commence detailed characterization and apply for a permit for construction of a deep repository, an integrated safety assessment must in any case be carried out. If all essential preferences are satisfied, this assessment should in all probability indicate that the deep repository possesses satisfactory safety and that good conditions exist for successful execution of the civil engineering works.

Function analyses and concerned parameters

In the column headed "function analyses", the analyses (calculations etc.) that can be used to analyze the function are specified, along with which parameters are primarily taken into account in such an analysis. After completed function analyses, the requirements and preferences can be more precisely defined.

3.4 Requirements and preferences regarding parameters

On the basis of identified requirements and preferences regarding the function of the deep repository, the extent to which it is possible to formulate requirements or preferences directly on the parameters that determine function is analyzed.

3.4.1 Geoscientific parameters

SKB has identified parameters of importance to determine during geoscientific site investigation /Andersson et al., 1996/. The parameters are classified according to the geoscientific disciplines: geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry and transport properties. This report has also been translated to English /Andersson et al., 1998a/, with some marginal changes and a few supplementary figures. The parameters presented in the report include all siting factors presented in /SKB, 1994/. /Andersson et al., 1996 and 1998a/:

- identifies, describes and evaluates geoscientific parameters that are of importance to know in order to be able to carry out performance and safety assessments of a deep repository, and that can be obtained from a site investigation,
- discusses how identified parameters are used and which site-specific measurements can be employed to determine the parameter in question,
- presents and discusses data needs for rock engineering,
- presents and discusses data needs for description of other environmental aspects,
- presents other data needs for analysis and a general understanding of geoscientific conditions.

It is also observed that few geoscientific parameters are measured directly, but are rather often determined by means of an interpretation procedure which can give rise to various errors and uncertainties. Measurement error comprises only a small portion of this uncertainty. Problems related to scale-dependent parameters and spatial variation can give rise to more significant uncertainties. The relevance of various geoscientific parameters therefore needs to be considered in relation to the methods of measurement and evaluation that are available for determining the parameter. Most tests that are performed in the field (e.g. injection tests, hydraulic fracturing, tracer tests etc.) provide indirect information on e.g. hydraulic conductivity, rock stresses or retention properties.

3.4.2 Determination of geoscientific suitability indicators

The suitability indicators comprise a subset of all the geoscientific parameters presented by /Andersson et al., 1998a/. The geoscientific suitability indicators are the parameters that significantly influence the functions of the deep repository. A systematic method has been used, just as in the process for determining detailed requirements on how the rock may influence the functions of the deep repository.

Structure for the work – tables

The parameters have been arranged by geoscientific discipline. Each discipline gives rise to a table whose rows correspond to the geoscientific parameters according to /Andersson et al., 1996/. The structure of the tables is shown by Table 3-3. The tables are presented in their entirety in Appendix B. The contents of the tables also comprise the main content of Chapters 4–9 in this report.

Table 3-3. Example in tabular form of the structure used to identify and explain geoscientific suitability indicators. The example is taken from the discipline chemistry (hydrogeochemical composition) and the parameter TDS (Total Dissolved Solids). Clear requirements could be formulated for this parameter. The complete chemistry table is shown in Appendix B.

Geoscientific parameter	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator?	Criteria during feasibility study (FS) and site investigation (SI)
TDS (total dissolved solids)	TDS<100 g/l at repository level		Around 1,000 m depth 0–35 g/l. Up to 100 g/l has been measured at 1,700 m depth.	Yes	FS: no (but attention in coastal areas) SI: Quality-approved measured TDS concentrations at repository level must meet requirements. Occasional higher values can be accepted if it can be shown that the water is located in areas that can be avoided.

Each table is divided into the following columns (see Table 3-3):

- reference to function in function table,
- requirements regarding parameter,
- preferences regarding parameter,
- value range in Swedish bedrock,
- usefulness as suitability indicator, and
- criteria.

The column that refers to the description of functions and analyses in the function table has been omitted for reasons of space. Information on how the geoscientific parameter in question enters into different function analyses is given in this column. The column is, however, included in the complete tables presented in Appendix B.

Requirements regarding value ranges for parameter

Wherever possible, requirements (regarding value ranges) are sought that can be directly related to individual parameters. In some cases it is possible to directly stipulate an impermissible value range for the parameter on the basis of requirements made on function. As a rule, it is difficult to relate requirements directly to geoscientific parameters. There are several reasons for this:

- the parameter is only one of several parameters that determine a function, and the suitable value range depends on the value of the other parameters,
- the parameter may influence several functions, and it is not certain that value ranges that are suitable for one function are also suitable for other functions,
- the parameter influences a function that is "only" a preference according to the function table.

Preferences regarding value ranges for parameter

Preferences regarding values ranges for the parameter in question are given in this column. The reason for giving preferences instead of requirements has been explained above. Preferences are supposed to provide guidance on what is needed in order for a performance or safety assessment to result in satisfactory conditions. The preferences may thereby relate to value ranges for the parameter that result in a desired function, but do not have to define the exact limit for unacceptable function, since such a limit is in many cases relative, unknown or can be influenced by modification of the repository layout.

In preparation for a decision to commence detailed characterization and apply for a permit for construction of a deep repository, an integrated safety assessment must in any case be carried out. If all essential preferences are satisfied, it is highly probable that this assessment will indicate that the deep repository possesses satisfactory safety and that the construction analysis will indicate good constructability.

Value range in Swedish crystalline bedrock

In cases where general knowledge exists regarding the parameter's value or value range in Swedish crystalline bedrock, this has been documented. Value ranges are discussed for all geoscientific parameters and not just for the selected suitability indicators.

Usefulness as suitability indicator

The main purpose of the table as a whole is to systematically ascertain whether the geoscientific parameters at any stage during the siting work can be a possible suitability indicator. In ongoing projects, a geoscientific parameter is a useful suitability indicator if one of the following conditions is fulfilled:

- a direct requirement or an essential preference has been formulated for the parameter, or
- the parameter is expected to have a great influence on the result of one or more important function analyses.

The parameter must furthermore be able to be determined during feasibility studies or site investigations. A brief explanation, based on the above rules, is included in the table for each parameter, see Appendix B.

Knowledge level in different siting or investigation stages

Based on the list of possible siting factors, the level of knowledge that can or should be reached in a feasibility study, site investigation and detailed characterization is discussed. It is not reasonable to designate a parameter as a suitability indicator if the parameter cannot be measured or otherwise estimated.

To be able to indicate whether a parameter is a useful suitability indicator, but above all to be able to specify criteria during and after a given investigation stage, knowledge is needed concerning what precision can be expected in the parameter estimation. Knowledge of the parameter increases from the feasibility study (FS) to the site investigation (SI) and detailed characterization (DC). However, the importance of the different investigation stages varies greatly between different parameters. Naturally, the ambition level for the different investigation stages can also influence the extent to which a parameter can be determined.

Table 3-4. Example of how knowledge of a geoscientific parameter changes as the siting work progresses. Of the parameters in the table, it is only for topography that full knowledge is achieved already during a feasibility study.

Geoscientific parameter	Knowledge during feasibility study (FS)	Knowledge during site investigation (SI)	Knowledge during detailed characterization (DC)
TDS (Total Dissolved) Solids	Generic	Site-specific information from deep boreholes, sufficient to characterize the repository area.	May contribute new knowledge on TDS in the low-permeable rock, but also entails a risk of disturbances.
Topography	Full knowledge on regional scale	Full knowledge	Full knowledge
Location, size, direction of fracture zones and fractures	Location of regional zones on surface can be judged	Reasonable precision for regional and local major fracture zones. Stochastic information on local minor fracture zones and fractures (frequency, orientation, size)	High precision for regional and local major fracture zones in the repository area. Fair for local, small ones. Stochastic information on fractures. Knowledge of location of fracture zones and fractures at tunnels.
Permeability for rock mass	Generic for selected geology	Spatial distribution and mean values	Direct knowledge near tunnels.

It is not always possible to quantify the expected precision in a simple manner. However, it is possible to discuss precision qualitatively; Table 4-3 illustrates this with an example. Such a qualitative discussion is valuable as a basis for deciding which criteria can be linked to a given parameter at a given investigation stage. Based on information of this kind, it is then possible to judge when the suitability indicator will be applicable.

Criteria

See the next section regarding criteria.

3.5 Criteria

Criteria are formulated for the parameters that are judged to be useful as suitability indicators. The criteria shall be able to be used to judge whether a site satisfies or does not satisfy stipulated requirements, and to what extent preferences are satisfied. Above all, the criteria are aimed at ensuring that unsuitable sites are excluded, which is in keeping with the general recommendations issued by the IAEA /IAEA, 1994/. The final judgement as to whether a repository at a given site is safe is, however, made in an integrated safety assessment. An integrated construction analysis is carried out to judge the scope and consequences of the civil engineering works. The criteria provide guidance on the outcome of the analysis. The criteria may change during the course of the siting work, since the information on sites changes, but requirements and preferences remain the same.

3.5.1 Siting stages and criteria

Criteria are formulated for the stages prior to and during site investigation. The criteria need to be linked to the information that is available at the current stage of the siting work and to the decision-making situation in which they will be used.

- Prior to a site investigation it is important to be able to rule out obviously unsuitable areas and identify areas that should be prioritized for further investigations, i.e. areas where there are good prospects that the site investigations will show that the rock has suitable properties. Criteria should not be made too strict at this stage, in view of the limited information that is available on the properties of the rock at depth. The criteria will be used to select suitable areas for site investigations. An evaluation of whether all requirements and preferences are satisfied has the character of an overall forecast.
- During a site investigation, it must be possible to show with great certainty whether a site is suitable or unsuitable as a deep repository site. Further, it may be meaningful to use criteria to compare sites. When the site investigation is finished, the suitability of the sites is determined in an integrated evaluation within the framework of an integrated safety assessment and an integrated construction analysis. During the site investigation, site-specific data shall, in relation to the previously specified criteria, provide good guidance on what such an integrated assessment is expected to result in.

The criteria are based on the importance of the different suitability indicators and an assessment of the precision of the available information. They are formulated to serve as a basis for SKB's different decisions prior to and during the site investigation and to clarify the underlying data. They do not take the place of the overall assessments that need to be made by SKB, competent authorities and other decision-makers.

3.5.2 The work of formulating criteria

The work of formulating criteria has started with all identified suitability indicators and is primarily aimed at verifying whether a site is suitable or unsuitable. Based on the estimated information quantity and decision situation before and during the site investigation, the already identified suitability indicators are analyzed by asking the following questions:

- Which precise and quantified criteria can be meaningfully used for the selection of areas for site investigations? What are the consequences of criteria not being satisfied?
- Which precise and quantified criteria can be meaningfully used during the site investigations and for selection of a site for detailed characterization? What are the consequences of criteria not being satisfied?
- Can safety or technical suitability only be judged in terms of a site-specific function analysis or construction analysis? If so, which analysis needs to be done and what are the consequences of different outcomes of such an analysis?
- Is it possible to say whether certain outcomes, within the suitable range, of parameter estimates or of function analyses are better than others? Do these outcomes entail a substantial improvement of function, or is the improvement of subordinate interest?

Table 3-5. Two examples of the relationship between requirements, suitability indicators, knowledge level and criteria. Requirements relate to actual conditions regardless of siting stage. Criteria are an application of suitability indicators in a given stage as a basis for decision. The complete criteria formulations are presented later in the report.

	General siting studies	**Feasibility studies**	**Site investigation**	**Detailed characterization**	**Operation**
Requirement: No dissolved oxygen in groundwater at repository level					
Knowledge	Generic	Generic	Site-specific information from deep boreholes, which is sufficient to characterize the repository area.	May contribute new knowledge in the low-permeable rock, but also entails a risk of disturbances.	May ontribute new nowledge in the low-permeable rock, but also entails a risk of disturbances.
Suitability indicators	–	–	Eh, [Fe^{2+}] and [HS^{-}] as indicators of the absence of dissolved oxygen.	–	–
Examples of possible criteria	No criteria	No criteria	At least one of the indicators low Eh, occurrence of Fe^{2+} or occurrence of HS^{-} must be satisfied. Otherwise the site must be abandoned.	–	–
Requirement: Deposition holes may not be intersected by fracture zones					
Knowledge	Location of regional zones at surface can be judged	Location of regional zones at surface can be judged	Reasonable precision for regional and local major fracture zones. Stochastic information on local minor fracture zones and fractures (frequency, orientation, size)	High precision for regional and local major fracture zones in the repository area. Fair for local, small ones. Stochastic information on fractures. Knowledge of location of fracture zones and fractures at tunnels.	Knowledge of location of all fracture zones at deposition holes.
Suitability indicators	Location, orientation, length and width of regional fracture zones.	Location, orientation, length and width of regional fracture zones and local, major fracture zones.	Location, orientation, length and width of fracture zones and fractures.	Location, orientation, length and width of fracture zones and fractures.	Length, orientation, length and width of fracture zones and fractures.
Examples of possible criteria	Large homogeneous areas with large distance between regional fracture zones are of interest for further studies.	Further studies suitable in areas with such large distances between interpreted regional fracture zones that they accommodate a repository.	Revise layout based on new knowledge. If the repository does not fit (is split into a number of parts),another site should be chosen.	Unsuitable location for deposition tunnels can be avoided.	Direct verification of requirement impossible. Unsuitable positions for deposition holes can be avoided.

An example of a quantified criterion might be a range of values or a median value with variation measure. An example of a function analysis might be calculation of groundwater flow or retention capacity. An example of the consequences of a criterion's not being satisfied might be that the site is directly judged to be unsuitable, but might also be that there is a need for a performance assessment, an integrated safety assessment, an integrated construction analysis, or a better body of data to judge the suitability of the site. A modified repository layout might also be considered to achieve the desired safety functions.

For certain already identified suitability indicators, for example those that pertain to indications of dissolved oxygen in the groundwater at repository level, it is simple to specify clear criteria. For other indicators, such as those that have to do with the retention capacity of the rock, the criteria are more complex, since they affect different functions in different ways; they exhibit considerable spatial variability, and analysis of field data therefore often entails extensive modelling work. The work of defining criteria will therefore not lead to defined value intervals for all suitability indicators. However, for each indicator it shall be clearly evident how the information is dealt with in the safety assessment or construction analysis. In cases where defined criteria cannot be specified at the parameter level, the reason for this shall be given.

The term "criteria" is further elucidated in Table 3-5, where possible criteria in different stages of the process leading to a deep repository are specified.

Note that criteria at certain stages can also be based on suitability indicators that have not been subject to requirements. This is the case, for example, for preferences regarding the thermal conductivity of the rock. Good thermal conductivity is advantageous, and this suitability indicator can therefore be a basis for a criterion at early siting stages. Satisfaction of this preference leads to lower costs, since the repository can be made smaller. If the preference is not satisfied, however, this can be compensated for by modifying the repository layout so that the overall safety requirement is nevertheless met (low thermal conductivity is compensated for by greater spacing between the canisters in the deep repository).

3.5.3 Comparison between sites?

It is only in certain cases that the criteria can be used directly to compare sites. If the requirements are not satisfied on one site, but are on another, it is obvious that only the latter site can be considered for further studies. To compare sites where both all requirements and a large number of preferences are satisfied, the integrated comparison becomes more complex. The environmental impact assessment, an integrated safety assessment and an integrated construction analysis comprise essential background material in the integrated assessment of whether a site is suitable, see Chapter 2. Replacing the integrated assessment with simpler methods, such as weighting points for different parameters, could lead to oversimplification of the safety assessment and construction analysis, and there is a great risk that "point methods" could lead to a misleading result. The criteria presented in the report should, however, provide good guidance on the outcome of the integrated assessments.

- Certain criteria, linked to requirements, are so strict that the site must be abandoned or the repository concept substantially modified if the criteria are not satisfied.
- If a site has many properties that lie within the favourable value ranges according to the criteria, this is a great advantage since it is then very likely that the safety assessment will show that safety can be achieved with a wide margin to safety goals.
- There is no reason to rank sites from a safety viewpoint if the safety assessment shows that the safety goals can be achieved with a reasonably wide margin on these sites. A further comparison of how the sites satisfy safety-related criteria is thereby not meaningful.

It deserves to be emphasized that it is virtually impossible to formulate criteria that lead to the "best site". Naturally, all conceivable requirements must be satisfied, and a site that has many advantageous properties is probably "better" than a site with few advantageous properties. What is best in an absolute sense is, however, not self-evident, since many different sets of parameter values can lead to the same function. When comparing different sites it is also necessary to bear in mind that most of the rock's properties vary sharply in space and that they can only be determined with a given precision. After a selection, as described above, of suitable sites in the Swedish crystalline bedrock, it will most likely turn out that any differences between the suitable sites do not appreciably affect function. Furthermore, the difference in many properties will scarcely be statistically significant.

4 Geology

4.1 Geological conditions that influence the function of the deep repository

The description of the geology of an area can be divided into a description of soils, rocks and deformation zones in the rock. Geology determines the area's mechanical, thermal, hydraulic and chemical properties. The geological information on a site is used primarily as a basis for determining these properties, but there is some geological information that directly influences the function of the deep repository. It is these latter conditions that are discussed in this chapter. The influence on function and associated requirements and preferences are summarized in Table A.1 in Appendix A.

4.1.1 Influence on canister integrity

Stable geological conditions are needed to ensure the mechanical stability of the canister. The chosen deep repository concept with location in crystalline basement generally satisfies this preference. More specific requirements and preferences are mainly derived from discussions of the rock's mechanical, thermal, hydraulic and chemical properties and are therefore discussed in the following chapters (Chapters 5–9). To make sure the deep repository is sited in particularly stable areas in the rock, the repository should be positioned so that the disposal tunnels avoid major deformation zones in the rock as much as possible. The deformation zones indicate that alterations or movements have taken place at some time in the area's geological evolutionary history. The zones usually have reduced strength and increased permeability.

To obtain a consistent terminology that can be unambiguously understood by representatives of all disciplines, SKB uses the terms "plastic shear zones" and "fracture zones" to designate zones where the deformation has been plastic and brittle, respectively. Sections 4.5 and 4.6 provide stricter definitions of these terms, as well as an analysis of what requirements and preferences can be made regarding the positioning of the deep repository in relation to different types of deformation zones.

4.1.2 Influence on the isolating capacity of the buffer

Stable geological conditions are also desirable so that the buffer can retain its isolating and sealing capacity. Requirements and preferences regarding the geological conditions are similar to those that can be derived from requirements and preferences regarding how canister function can be ensured (see above). There are no further requirements and preferences, except for the more specific requirements and preferences regarding the mechanical, thermal, hydraulic and chemical properties of the rock (see Chapters 5–9).

4.1.3 Influence on the isolating and retarding capacity of the rock

The deep repository's isolation could be breached if other underground activities are conducted at great depths in the repository area in the future. The meaning of "intrusion" is dealt with in SR 97. The least acceptable distance depends on the scope of the activities. The likelihood of future underground activities is judged to be linked to ore potential, occurrence of valuable minerals, occurrence of unusual rock types and assessment of other competing interests. Requirements and preferences can thereby be linked to the area's rock type distribution (see section 4.4).

In order for the rock to have good and predictable retention capacity, stable and homogeneous geological conditions are desirable. Requirements and preferences regarding the geological conditions are similar to those that can be derived from requirements and preferences regarding how canister function can be ensured (see above). There are no further requirements and preferences, except for the more specific requirements and preferences regarding the mechanical, thermal, hydraulic and chemical properties of the rock (see Chapters 5–9).

4.1.4 Biosphere-related matters

Biosphere-related matters are dealt with in section 7.5.

4.1.5 Construction-related matters

The following principles apply to rock engineering and construction of the facility:

- the working environment shall be safe,
- the environmental impact of investigations and construction shall be limited and kept within acceptable limits,
- construction shall only have a limited and transient impact on the safety functions of the deep repository, and construction and deposition shall be able to be conducted simultaneously,
- it is preferable that the construction work can be carried out with as few interruptions as possible and with limited use of extraordinary reinforcement (rock support) and sealing measures (good constructability),
- to facilitate investigations, construction and operation, it is preferable that the deposition area does not have to be split into a large number of subareas and that it is possible to position deposition tunnels in a flexible manner.

The layout of the repository is governed to a large extent by the geological information. The methodology chosen by SKB of configuring the repository so that the deposition tunnels avoid major deformation zones in the rock as far as possible (see sections 4.5 and 4.6) also facilitates achieving the above requirements and preferences. More specific construction-related matters are discussed in coming chapters, mainly in Chapter 5 (rock mechanics) and in Chapter 7 (hydrogeology).

4.2 Topography

4.2.1 Description of parameter and its influence on functions

Topography, including other geodetic information, constitutes essential basic information on a site.

Detailed topographical information is utilized to identify fracture zones on different scales. The information is therefore indirectly of essential importance for judging the isolating properties of the rock and the groundwater flow in the rock.

On a regional scale, the topography is often assumed to provide boundary conditions for the groundwater flow in the repository area (see further section 7.6). The bottom topography of the sea and lakes is also of importance in assessing the influence of sea level changes. The topography influences the near-surface water flux and is therefore of great importance for conditions in the biosphere. The bottom topography of lakes and watercourses is needed in determination of volumes in biosphere models and in determination of future changes.

4.2.2 Requirements and preferences

A small regional topographical gradient is desirable from a hydrogeological point of view, since it limits the size of the hydraulic gradient. This preference is discussed further in the chapter "Hydrogeology", section 7.6.

4.2.3 Generic knowledge and knowledge obtained at different stages

According to RD&D-Programme 95 /SKB, 1995a/, the topographical gradient normally lies within the range 0.1–1% on a regional scale. Higher values occur mainly in the Caledonides (mountain range in northern Sweden).

Topographical information can be requisitioned from the National Land Survey. In conjunction with a site investigation, however, additional data are needed for greater detail. This also applies to the bottom topography of lakes, watercourses and any concerned marine areas.

4.2.4 Suitability indicators and criteria

The topography primarily comprises basic information for the general geoscientific description and can therefore not in itself comprise a useful suitability indicator.

4.3 Soils

4.3.1 Description of parameters and their influence on functions

By "soils" is meant loose deposits that form the soil layer on top of the bedrock. Loose deposits on lake and sea beds are also counted as soil cover in this context. The topsoil is the uppermost layer of the soil cover that has been altered by the influence of weather, vegetation, fauna and man.

In general, the soil cover is of limited importance for the isolating and retarding functions of the deep repository. The most important functions are that the soil cover contributes to oxygen-free conditions in the superficial bedrock (by bacterial reduction) and that peat mosses, as well as sediments on lake and sea beds (mainly clays), can absorb radionuclides. The thickness of the soil cover, as well as the occurrence of bottom sediments, also influences the boundary conditions for groundwater flow in the rock, but this influence is of limited and indirect importance. Studies of the soil cover can give indications of postglacial movements (neotectonics). The indications may be shoreline displacements or indications of the occurrence of seismites (soils that show clear signs of having lost their bearing capacity on some previous occasion). It is essential to determine whether postglacial movements may have occurred in an area. If there are indications of such movements, this influences the assessment of the area's long-term mechanical stability.

The properties of the soil cover are included in the safety assessment's description of the transport of radionuclides in the biosphere (see e.g. SR 97, Main Report, section 9.9 /SKB, 1999a/). The soil cover influences the near-surface transport of radionuclides, particularly via its capacity to absorb and accumulate radionuclides. The aggregate dose consequence depends on many different factors, however, and is above all determined by whether release to the biosphere occurs at all. It is necessary to be familiar with the properties of the soil cover in order to be able to carry out the analysis, but the biosphere has no safety function (see Chapter 2) and there are thereby no grounds for making requirements or preferences regarding the properties of the soil cover from this point of view.

During a site investigation, the soil cover is an obstacle to ascertaining conditions in the underlying bedrock from the ground surface. The thickness of the soil cover and the distribution of soil types are also of importance for repository layout. Tunnel portals can, for example, be more complicated to execute with thick soil layers. This can influence costs, but is of no importance from a safety viewpoint.

4.3.2 Requirements and preferences

There are no requirements associated with soil types or the thickness of the soil cover.

There are, on the other hand, several preferences regarding conditions that simplify the site investigations. These are that there should be a high proportion of exposed rock and otherwise moderate soil depth (preferably less than about 10 m), since this makes it easier to ascertain conditions in the underlying bedrock from the ground surface. It is further an advantage to avoid bouldery and waterlogged terrain, clay areas and agricultural lands.

4.3.3 Generic knowledge and knowledge obtained at different stages

Soil conditions vary widely in Sweden. The dominant soil type in Sweden is glacial till (approx. 75%). There is also a great deal of glaciofluvial and alluvial sediments. Fine sediments have differing origins and may be glacial, postglacial or marine. The soil cover frequently shows signs that swelling processes have taken place. Nevertheless, the preferences expressed above are satisfied at a very large number of places. Experience from study site investigations shows that extensive and thick soil covers present difficulties in the continued interpretation work.

A feasibility study usually provides a good overall picture of occurring soil types and their thicknesses. A detailed picture is obtained from site investigations.

4.3.4 Suitability indicators and criteria

Soil type information can be of some importance for choosing between sites in the stage prior to a site investigation. Special criteria during the site investigation are not needed.

4.4 Rock types

4.4.1 Description of parameters and their influence on functions

In the earth's crust, combinations of elements form different minerals. Relatively few of these minerals constitute the main constituents in our most common rock types. Most of the bedrock in Sweden consists of ancient crystalline rock types such as granite, gabbro and gneiss.

The principles for classifying rock types are complex. For example, the designation "granite" refers to a rock of a given mineral composition, while "gneiss" is a structural term. A gneiss can thus very well have a granitic composition. Requirements and preferences regarding rock types are made based on their properties and composition. In each specific case of a site investigation, the designations used for the rocks are defined, along with the mineral compositions of these rocks.

The importance of the rock types for a deep repository lies mainly in the fact that they have different thermal and mechanical properties (thermal conductivity, strength, stiffness, etc.). These properties in turn influence constructability and the thermo-mechanical influence of the heated repository, including how the heat spreads. Indirect information on the strength of the rock is often provided by parameters that have to do with the rocks' grain size, mineral composition and mineralogical alteration/weathering. Requirements and preferences regarding rock types from this perspective are discussed in Chapter 5 (rock mechanics) and Chapter 6 (thermal properties).

Differences in the strength, structure and geological history of rocks have led to different fracture systems in different rock types. For example, granites often exhibit a regular fracture system, while the fractures in gneisses are often controlled by the structure of the rock. In general, rock type boundaries, such as for example the boundary between dykes (e.g. diorite) and country rock, constitute potential zones of weakness in the rock. This is because the different physical properties of the rock types also influence their capacity for deformation to differing degrees. It is therefore easier to describe the rock if the bedrock is homogeneous with few rock types.

The fracture system in turn influences other parameters that have to do with the strength of the rock mass and the groundwater flow through the rock mass. Besides variation between rock types, the fracture pattern also varies within the same rock type and between different parts of the rock mass. Requirements and preferences regarding the mechanical and hydraulic properties of the fractures are discussed in Chapter 5 (rock mechanics) and Chapter 7 (hydrogeology).

The rock types also influence the composition of the groundwater. The oxygen in percolating groundwater is consumed by oxidation of the minerals (see Chapter 8). The minerals can also control pH, Eh and other chemical parameters, such as carbonate content, by means of different buffering reactions. The difference in rock type composition in the crystalline Swedish basement does not, however, give any reason to make special requirements or preferences regarding rock type composition from this aspect.

Sorption on fracture-filling minerals can limit the mobility of radionuclides in the rock mass, but the influence is limited. In SR 97, it is pessimistically assumed that the transport of radionuclides is not retarded by sorption in fracture-filling minerals. There are therefore no grounds for making requirements or preferences regarding fracture-filling minerals. However, knowledge of fracture-filling minerals is essential for building up a geoscientific understanding of the site.

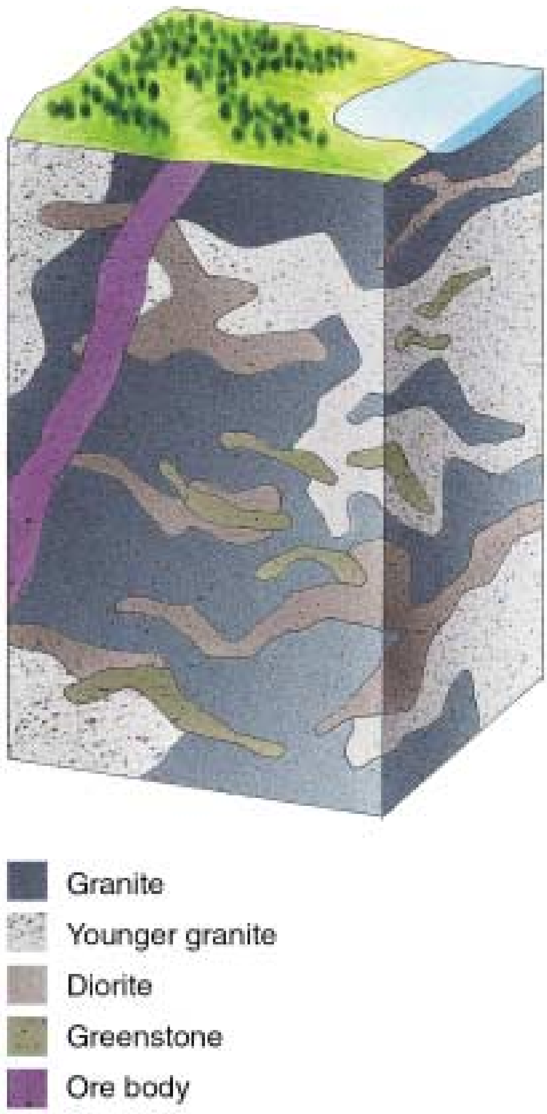

Figure 4-1. *The rock types in the repository's deposition area must not have ore potential, i.e. consist of such valuable minerals that this could justify mining at a depth of hundreds of metres. Another factor to consider is that inhomogeneous bedrock requires greater investigation efforts with more boreholes than a homogeneous one.*

Certain rock types are of interest as natural resources. There may, for example, be acid volcanites, which in many regions are ore-bearing and thereby unsuitable for a deep repository. Other rock types may be of interest for extraction of industrial minerals or as utility stone. Since it can be difficult to predict the possible uses of different rock types in the future, it is an advantage if the deep repository is sited in commonly occurring rock types, above all granite and gneiss.

Very high concentrations of uranium-bearing minerals may make particularly great requirements on ventilation in the repository to keep the radon concentration at a sufficiently low level.

4.4.2 Requirements and preferences

It is a requirement that the rocks in the deposition area not have ore potential, see Figure 4-1, i.e. consist of such valuable minerals that this could justify mining at a depth of hundreds of metres.

Since it can be difficult to predict the possible uses of different rock types in the future, it is an advantage if the deep repository is sited in commonly occurring rock types. Furthermore, it is desirable that the bedrock be homogeneous with few rock types, since this simplifies calculations and forecasts of thermal, mechanical, chemical and hydraulic conditions in the repository area. For more specific requirements from these perspectives, see Chapters 5 and 6.

It is an advantage if the rock contains few minerals that emit radon, but a satisfactory working environment can always be achieved by means of various ventilation measures.

4.4.3 Generic knowledge and knowledge obtained at different stages

Information on rock type distribution in Sweden is compiled on geological maps published by the Geological Survey of Sweden (SGU). The information is supplemented in conjunction with regional general siting studies /e.g. Stephens and Johansson, 1999ab/.

Knowledge of principal rock types in the superficial bedrock is usually already good at the feasibility study stage. Detailed knowledge of rock type distribution at greater depth is obtained during the site investigations.

4.4.4 Suitability indicators and criteria

Rock type distribution is an important suitability indicator, among other things for judging whether the repository area meets the requirement of not having potential for the occurrence of ore or industrial minerals. Rock type distribution is also used to assess certain mechanical and thermal suitability indicators (see Chapters 5 and 6).

The above requirements and preferences may be satisfied on a large number of sites in Sweden. In the regional general siting studies /e.g. Stephens and Johansson, 1999ab/, areas are indicated which can be regarded as potentially suitable/unsuitable on a regional scale from this viewpoint, among others. More detailed knowledge exists in the feasibility study municipalities. After completion of the feasibility study, continued studies and investigations are only performed on areas not judged to have potential for the occurrence of ore or valuable industrial minerals and judged to be homogeneous and consist of commonly occurring rock types.

The same criteria are used during the site investigation, except that the forecast of rock type distribution now contains fewer uncertainties. This permits a more local adaptation of the repository. If extensive occurrence of ore-bearing minerals or valuable industrial minerals is encountered, the site should be abandoned.

4.5 Structural geology – plastic shear zones

4.5.1 Description of parameters and their influence on functions

Over the course of the millennia, the bedrock has been subjected to forces and temperatures that have partially melted and deformed it. Deformation and alteration have taken place during certain periods, which have been separated by much longer periods with much calmer geological conditions. The evolutionary process has been fairly complex and exhibits regional differences /Larsson and Tullborg, 1993/.

This deformation has created deformation zones in the rock. A deformation zone is a zone of weakness in the bedrock in which there is considerably greater deformation than in the surrounding rock mass. The deformation may have been plastic (see below) or brittle (see 4.6). For a more thorough discussion, see /Bergman et al., 1999/.

If the temperature and the pressure have been high enough, the deformation has taken place plastically, i.e. without brittle fractures. A large fraction of the older bedrock in Sweden was deformed plastically between 1 000 to 2 000 million years ago. It lay at great depth in the earth's crust, up to several tens of km, with temperatures of up to 500–600°C or more. As a result of these deformations, the bedrock was folded and different linear and planar structure (fold axes, schistosity, veining) were formed. The deformations have also resulted in persistent plastic shear zones, which may contain the rock type mylonite.

If an area is classified as a regional plastic shear zone, this indicates that the area has been subjected to heavy deformation, which may in turn have given rise to heterogeneous bedrock. This deformation may have created zones of weakness in the bedrock in which reactivation under brittle conditions has given rise to water-bearing fracture zones, and which may be associated with reduced mechanical strength.

4.5.2 Requirements and preferences

In selection of areas for site investigations, there is a requirement that regional plastic shear zones be avoided, unless it can be shown that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be "tectonic lenses" in the vicinity of regional plastic shear zones /SKB, 1997/ where the bedrock is homogeneous and relatively unaffected. There is no obstacle to siting the repository within such lenses, provided they are large enough and the rock there otherwise has suitable properties.

See also requirements and preferences for fracture zones.

4.5.3 Generic knowledge and knowledge obtained at different stages

Knowledge regarding the occurrence of plastic shear zones is obtained in the regional general siting studies (e.g. /Stephens and Johansson, 1999ab/) and in feasibility studies (e.g. Östhammar /SKB, 1997/). Plastic shear zones are as a rule identified by remote analysis (e.g. aeromagnetic surveys, satellite pictures, etc.) combined with data on planar structures (gneissosity, schistosity) in the bedrock. Interpreted zones are verified by geological field mapping. Above all in areas with a high proportion of exposed rock, knowledge of vertical plastic shear zones is already good at the feasibility study stage, while means are not available to find subhorizontal zones. Knowledge is poorer in soil-covered areas, but satisfactory information can often be obtained from aeromagnetic surveys and from the regional geological picture. It should be possible to obtain good knowledge of the plastic shear zones during site investigations.

4.5.4 Suitability indicators and criteria

The above discussion shows that information on plastic shear zones is a useful geoscientific suitability indicator.

During the feasibility study, the study site is adjusted so that regional plastic shear zones are avoided. If sufficient repository volume cannot be obtained on the remaining area, the site is unsuitable.

The increased knowledge obtained in the site investigation regarding the location of the plastic shear zones and the properties of the shear zones is used to devise a site-adapted rock cavern layout. If the repository cannot be configured in a reasonable manner, i.e. if it has to be split up into a large number of parts, another site must be chosen.

4.6 Structural geology – Fracture zones and fractures

4.6.1 Description of parameters and their influence on functions

By "fracture zones" is meant deformation zones where the deformation has been of a brittle character, i.e. a mechanical fracturing of the rocks. Such deformations have occurred higher up in the earth's crust where temperatures and pressures are lower than in the case of plastic deformation. Fracture zones generally have a lower mechanical strength and a higher permeability than the rest of the rock. The occurrence of fracture zones is therefore of direct importance for the rock-mechanical (Chapter 5) and hydrogeological (Chapter 7) description of a site.

Strict classification into brittle and plastic deformation zones is not possible, since there are intermediate forms. Furthermore, different names are used for different types of deformation zones. A fault is a fracture zone along which movements have taken place. The term "lineament" is used for an unspecified, topographically and/or geophysically distinguishable linear structure in the landscape. Nor is the terminology consistent in different engineering fields. Words such as "structure", "zone of weakness" or "discontinuity" are often used to designate fracture zones. To obtain a consistent terminology that can be unambiguously understood by representatives of all disciplines, SKB uses the term "fracture zones" to designate all different types of deformation zones where the deformation has been of a brittle character. If only indirect information exists on the occurrence of a fracture zone, for example a valley or a geophysical anomaly, SKB uses the terms "lineament" or "interpreted fracture zone".

SKB has further chosen to classify fracture zones according to length (size) and use the designations "regional fracture zones", "local major fracture zones", "local minor fracture zones" and "fractures" (see Table 4-1). Due to the often complex structure and geometry of fracture zones, the borderlines are somewhat fluid depending on the scale and the purpose of the investigations. Regional fracture zones and major local fracture zones can often be determined deterministically. By this is meant that the locations of the fracture zones can be established during the site investigations. For minor local fracture zones and fractures, this is not possible in the entire rock mass surrounding a repository. Instead, statistical descriptions of their locations and properties are used. Interpreted fracture zones often have to suffice for regional groundwater models.

Table 4-1. Classification and naming of the bedrock's brittle structures, and ambition level for geometric description during site investigation (length and width measurements are approximate).

Name	Length	Width	Ambition for geometric description
Regional fracture zones	> 10 km	> 100 m	Deterministic
Local major fracture zones	1–10 km	5–100 m	Deterministic (with uncertainties)
Local minor fracture zones	10 m–1 km	0.1–5 m	Statistical (some deterministic)
Fractures	< 10 m	< 0.1 m	Statistical

The length classification does not in itself constitute a ground for fracture zones of different sizes having different properties. To characterize a fracture zone, information is needed on its location, orientation, length and width, but also on its properties. The mechanical and hydraulic properties of the fracture zones and fractures is further discussed in sections 5.2 and 7.2. The regional and local major fracture zones have often been formed in connection with primary plastic zones. They are usually characterized by heavy schistosity with a high fracture frequency or by locally crushed, sometimes clay-altered sections. From a mechanical viewpoint, larger future deformations can generally be expected in large (long) fracture zones than in small (short) ones (SR 97, Process Report /SKB, 1999b/). Large fracture zones are furthermore usually more permeable than the surrounding rock, although there are individual fractures that are at least as water-bearing as major fracture zones.

Information on fracture zones and fractures is used directly to configure a layout for the deep repository. The work is done in steps. Corridors for access and transport tunnels and volumes for the deposition area are determined during the site investigation. The direction of the deposition tunnels is determined. However, a detailed layout in terms of e.g. exact coordinates for each deposition hole does not have to exist until the exact locations of the deposition tunnels have been determined. This is not done until during the detailed characterization stage or during repository construction.

In future studies, SKB will take into account whatever detailed information on individual fractures and minor fracture zones is obtained from investigations for development of investigation, transport and disposal tunnels in order to progressively refine the layout of the repository and the position of individual deposition holes. In safety assessments performed to date (e.g. SR 97), no credit is taken for this potential for improving repository layout by detailed adaptation of the layout to actual conditions.

4.6.2 Requirements and preferences

To avoid placing deposition holes in areas where there is a high risk of future deformations and high permeability, it is a requirement that deposition tunnels and deposition holes may not pass through or be located near regional and local major fracture zones, see Figure 4-2. This requirement does not apply to fracture zones that have been found to be mechanically and hydraulically similar to the surrounding rock. The requirement does not apply to access tunnels and transport tunnels.

It is a requirement that deposition holes should not intersect identified local minor fracture zones. It is therefore preferable to have a moderate density (fracture surface area per volume) of fractures and local minor fracture zones.

It is not possible to stipulate general requirements on the smallest acceptable distance between deposition tunnels and regional or local major fracture zones. The groundwater flow through the repository and the mechanical stability of the repository are dependent on the properties of the fracture zone and the surrounding rock, which means that mechanical and hydrogeological function always need to be evaluated for a particular layout. When devising repository layouts, however, SKB will use "respect distances" between deposition tunnels and identified regional and local major fracture zones. The respect distances are composed of a distance judged to comprise a suitable minimum distance between tunnel and fracture zone, plus a safety margin that compensates for the fact that the location of the fracture zones is not completely known. The judgement of what a suitable distance between tunnel and fracture zone is, as well as the size of the safety margin needed to manage the uncertainty in the location of the fracture zones, are dependent on the level of knowledge of the rock and thereby have more the character of criteria than strict requirements and preferences. The size of the respect distances is therefore discussed under the heading "criteria" below. Assumed respect distances will be used in conjunction with the stepwise site investigation and the design process (see below). But the real distances that are needed are determined by means of a site-specific function analysis.

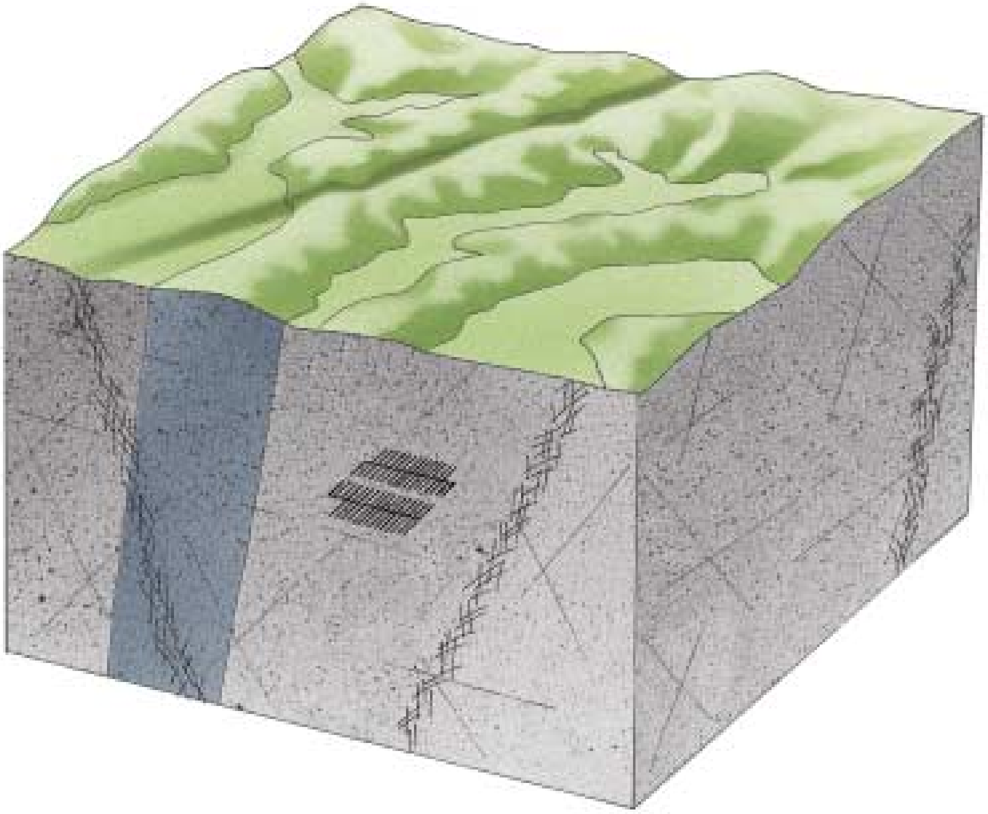

Figure 4-2. *Deformation over the course of the millennia has created deformation zones in the rock. A deformation zone is a zone of weakness in the bedrock in which the deformation is much greater than in the surrounding rock mass. The deformation may have been plastic or brittle (fracture zones). It is a requirement that deposition tunnels and deposition holes may not pass through or be positioned too close to regional and local major fracture zones.*

4.6.3 Generic knowledge and knowledge obtained at different stages

The occurrence of regional and local major fracture zones has been mapped with varying accuracy in different parts of the country. More targeted studies are conducted in conjunction with regional general siting studies /e.g. Stephens and Johansson, 1999ab/. Fracture zones for the sites analyzed in SR 97 are described by Rhén et al. (1997), Andersson et al. (1991) and Hermanson et al. (1997). Saksa and Nummela (1998) discuss the uncertainties in these descriptions.

The material that is available in a feasibility study permits a preliminary identification of regional fracture zones. The forecast is improved if the degree of exposure is high (see section 4.3.4).

Interpreted zones are verified by geological field mapping. Above all in areas with a high proportion of exposed rock, knowledge of vertical plastic shear zones is already good at the feasibility study stage, while means are not available to find subhorizontal zones. Knowledge is poorer in soil-covered areas, but satisfactory information can often be obtained from aeromagnetic surveys and from the regional geological picture.

The ambition level in site investigations is to describe all regional and local fracture zones deterministically, while local minor fracture zones and individual fractures can normally only be described statistically. The probability that there are undiscovered major fracture zones in the area also needs to be estimated.

4.6.4 Suitability indicators and criteria

Information on fracture zones and discrete fractures constitutes an important suitability indicator.

Candidate areas for further investigations are chosen in a feasibility study so that a deep repository can be positioned with good margin to the fracture zones identified in the feasibility study. Even though this can (almost) always be achieved by splitting the repository up into different parts, it is obviously desirable that the repository not have to be split up into too many parts. Available data must not indicate that the fracture zones are so dense that the repository would have to be split up into an unreasonably large number of parts. Possible investigation areas may only be intersected by a few regional fracture zones.

During the site investigation, the hypothetical repository is adapted to the then-identified zones. Suitable respect distances to identified regional and local major fracture zones can only be determined site-specifically, but are assumed to comprise at least several tens of metres to local major zones and at least 100 metres to regional zones. Information on the mechanical and hydraulic (permeability) properties of the zones and the adjacent rock mass is utilized. Depending on the properties of the fracture zones and the rock mass, this may necessitate increasing the distance to certain zones, while the distance to other zones may be decreased. The above guidelines for respect distance will, however, be used in the initial layout work. If the repository has to be split up into a very large number of parts, the site is not suitable for a deep repository.

It should further be noted that information on fracture zones and individual fractures is essential for analysis of the site's rock-mechanical (see 5.4) and hydrogeological (7.2) conditions.

4.7 Summary suitability indicators – geology

The preceding sections have provided an account of which geological suitability indicators may be relevant in different stages of the siting work. The complete account of the work is found in Tables A-1 in Appendix A and B-1 in Appendix B and is summarized in Table 4-2.

Table 4-2. Suitability indicators for geology (the complete account is found in Appendices A and B)

Parameters – groupwise	Requirements or preferences	Criteria during feasibility study (FS) and during site investigation (SI)
Topography	–	Important basic information, but not primary indicator. See hydrogeology.
Soils	Preference: small thickness and high proportion of exposed rock.	FS: – SI: Not relevant during site investigation.
Rock types	Requirement: no ore potential. Preferences: no valuable utility stone or industrial minerals, common rock type.	FS: Avoid areas with known ore potential and heterogeneous or unusual bedrock.
	(Indirect requirements/preferences from rock mechanics and hydrogeology).	SI: Local adaptation of repository with reference to indicator. If extensive occurrence of ore-bearing minerals is encountered, the site should be abandoned.
Plastic shear zones	Regional plastic shear zones are avoided, if it cannot be shown that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be tectonic lenses near regional plastic shear zone that can be suitable for a deep repository.	FS: Avoid known regional plastic shear zones. If sufficient repository volume cannot be obtained, another area must be chosen. SI: Revise layout according to new knowledge. If the repository cannot be positioned in a reasonable manner (if it would have to split up into a very large number of parts), another area must be chosen.
Fracture zones	Deposition tunnels and holes may not pass through or be located near regional and local major fracture zones. Assumed respect distances will be used in conjunction with the stepwise site investigation and the design process. But the distances that are really needed are determined via a site-specific function analysis.	FS: Choose area for continued studies so that a deep repository can be positioned with good margin in relation to the fracture zones identified in the feasibility study. The area is unsuitable if known fracture zones are so dense that a repository would have to be split up into an unreasonably large number of parts.
	Deposition holes may not intersect identified local minor fracture zones. Moderate densities (fracture surface area per volume) of fractures and of local minor fracture zones are also preferable.	SI: Suitable respect distances to identified regional and local major fracture zones can only be determined site-specifically but are assumed to comprise at least several tens of metres to local major zones and at least 100 metres to regional zones. If the repository cannot be positioned in a reasonable manner (would have to be split up into a very large number of parts) in relation to plastic shear zones, regional fracture zones or local major fracture zones, the site is not suitable for a deep repository.

5 Rock mechanics

5.1 Influence on the function of the deep repository

The mechanical properties of the rock influence both the isolating and retarding functions of the deep repository. The rock-mechanical properties are also of great importance for how the repository is configured and constructed. Generally speaking, the technical conditions for constructing rock caverns in the Swedish crystalline basement are good. Table A-2 in Appendix A summarizes how the mechanical properties of the rock influence the functions of the deep repository, and what requirements and preferences can be derived from this.

5.1.1 Overview

The rock is a mechanical system that is normally in static equilibrium under the prevailing loads. Disturbances of this equilibrium may be caused by load changes, e.g. due to excavation of rock caverns, or by changes in the mechanical properties of the rock. Instability leads to deformation of the rock mass, and failure can occur if the strength of the rock is exceeded. The failure state as such does not have to entail serious instability, however: small deformations, without consequences for performance and safety, can be sufficient for the system to regain equilibrium if failure should occur.

The mechanical disturbances take place during different epochs and in different parts of the rock. The disturbances also take place on different scales: firstly, there are different problem scales such as deposition holes, tunnels, the entire tunnel system, the rock volume around the repository; and secondly, the disturbances can cause both small-scale and large-scale changes. The geometric distribution of fracture zones and rock types and their mechanical properties determine where deformation and possible failures will occur. Movements take place preferably along fractures and fracture zones. Furthermore, different rock types have different strengths and different deformation properties.

The rock extraction that takes place during repository construction leads to an extensive change in the mechanical equilibrium, which leads to stress redistribution and deformations around the tunnels. If the stress levels are high relative to the strength of the rock mass, local failure can occur. This can occur rapidly in brittle rock types and is called “spalling” (stress induced failure). Furthermore, structurally induced failure occur when loose rock blocks fall out due to fracture geometry, the stress situation and the mechanical properties of the fractures and the rock. The conditions for construction in rock are therefore associated with a number of construction-related requirements and preferences.

The safety assessment is based on the initial state where the repository’s tunnels are built. The disturbances associated with rock extraction and civil engineering activities therefore have only an indirect influence on repository safety. Deposition will only take place in the tunnels that have been excavated in a satisfactory manner.

Changes in the geometry of the deposition holes could damage the buffer or canister. Extensive movements along fractures and fracture zones, or extensive formation of new fractures, could degrade the retention properties of the rock. The load cases that need to be taken into account are mainly changes in pore pressure on resaturation, the swelling pressure from the bentonite, thermal expansion of the rock, effects of earthquakes and effects of extensive climate change (such as glaciations). Furthermore, it is necessary to take account of the fact that the mechanical properties of the rock can change with time. Such changes in the near-field rock may be reduced friction or cohesion in fractures, loosening due to increased loading, or the fact that rock supports installed to stabilize the tunnel during construction and operation deteriorate with time (e.g. corrosion in rock bolts).

For a more thorough analysis of how rock-mechanical processes influence repository safety, see SR 97 Main Report and Process Report /SKB, 1999ab/.

5.1.2 Influence on canister integrity

If the deposition holes are deformed too much, the canister could be damaged. Calculations with a previous, less deformation-resistant design of the canister /Börgesson, 1992/ showed that rock movements on the order of 0.1 m do not lead to immediate canister failure. The canister design analyzed in SR 97 can take greater loads, so this canister should withstand greater deformations of the deposition hole. On the other hand, it is concluded in SR 97 Main Report /SKB, 1999a/ that due to various uncertainties in the assessment (creep deformation of the copper canister, velocity of the rock movement, etc.) the pessimistic criterion should be used that rock movements on the order of 0.1 m or more could lead to canister damage.

This criterion could naturally be changed with further changes in the canister design or the design of the deposition hole. The fundamental conditions that are advantageous or less advantageous for the mechanical stability of the repository are, however, not altered by minor changes in repository design. It is of course desirable that there be as little deformation as possible. In practice, this stability requirement is handled by not locating the deposition holes too close to the large fracture zones.

There is also a discussion in SR 97 Main Report /SKB, 1999a/ of whether the deposition holes could in the long term be deformed by creep movements in the bedrock. Such movements could occur if the mechanical properties of the host rock change with time so that movements take place due to already active stresses. The changes may be directly dependent on the state of stress, i.e. unstable growth of microfractures in intact rock. Uneven distribution of shear stresses along fracture planes on all scales can lead to initiation and growth of microfractures and eventually to local plasticization in connection with stress concentrations at irregularities in fracture surfaces. Knowledge is poor, but the attempts that have been made to analyze the process have indicated slow processes and small deformations.

5.1.3 Influence on the isolating and retarding capacity of the buffer

To preserve the isolating and retarding capacity of the buffer, deformation of deposition holes may not cause damage to the buffer. Such damage could only be caused by large deformations /Pusch and Börgesson, 1992/. Fracturing that gives rise to cavities around the deposition hole could also cause erosion of the bentonite. Deformations may not create such large cavities around the deposition hole that the buffer could swell without confinement and thus loose its swelling pressure. Nor may deformations of the deposition hole (instantaneous or cumulative) be so large that the diffusion distance through the buffer becomes too small. The mechanisms that could lead to deformations of the deposition hole have already been discussed in previous sections.

The fractures that intersect the deposition hole can, together with the hole wall, form loose blocks called wedges. If an overbreak occur, special measures are required to fill the spaces where the blocks were with bentonite. Block breakout is therefore not desirable, and extensive block breakout will make the deposition hole unusable. Similar problems can arise if the induced stresses on the boundary of the deposition hole exceed the compressive strength of the rock.

5.1.4 Influence on the retarding capacity of the rock

If fractures (and fracture zones) are deformed, their permeability changes because the fracture aperture changes. Formation of new fractures also affects permeability. Except in the immediate vicinity of the repository, however, these changes can be expected to be relatively small compared to the initially already very large spatial variation in the permeability of the fractures.

There are no mechanical requirements on the isolating and retarding functions of the rock. It is, however, desirable that deformation of rock mass and fracture zones should lead to negligible changes in permeability in relation to other uncertainties. This preference applies both on a local scale, around the deposition hole, and on the larger scale that represents the rock between the deposition hole and major fracture zones. Disturbances that influence permeability on a deposition hole scale can, in principle, occur for all conceivable load cases (see above), while disturbances that affect the rock on a larger scale could be caused by temperature changes and external loads caused by e.g. earthquakes or glaciations.

5.1.5 Construction-related matters

The repository is configured so that the probability of damage to the repository due to large deformations and faults is minimized. There are furthermore several rock-mechanical questions that must be taken into account in conjunction with construction and operation:

- All requirements on personal safety must be satisfied.
- Extensive rock burst, other major overbreak and collapse must generally be avoided.
- Extensive stability problems cannot be accepted in deposition tunnels or deposition holes, since this would prevent their being configured as planned.
- It is preferable that the civil engineering works can be carried out with as few complications as possible. (Potential reinforcement needs, downtimes etc. are investigated in conjunction with the design process.)
- If the repository area has to be split up into many subareas, separate investigations may be required regarding the possibilities of passing through the fracture zones that separate the areas.

The above requirements and preferences can as a rule be satisfied by means of a suitable repository layout, choice of siting depth and choice of execution methods. Due to increasing rock stress levels with increasing depth, constructability is much poorer at great depths /Winberg, 1996/. The repository layout is adapted to the regional and local major fracture zones (see sections 4.5 and 4.6) and to assessments of how tunnels should be oriented in relation to rock properties and states of stress (see e.g. /Munier et al., 1997/).

For the design process, information is needed on a variety of parameters to choose suitable execution methods and to be able to plan the work. If full-face tunnel boring is chosen, properties such as penetration index, drilling rate index (DRI) and wear properties should be determined. Furthermore, stress-induced failures in the tunnel contour can influence the feasibility of carrying out tunnel boring. Blastability should be assessed when choosing blasting method and explosive. None of these parameters are important for the choice of site, but can affect construction costs.

5.2 Initial rock stresses

5.2.1 Description of parameters and their influence on functions

The state of stress in the rock is a variable for all mechanical processes. The state of stress is a tensor and is characterized by three mutually perpendicular principal directions, each of which corresponds to a principal stress. If all three principal stresses are equal, the state of stress is isotropic and the principal directions are indefinite. If the principal stresses are unequal, the state of stress is anisotropic (deviatoric). The stability of the rock-mechanical system is dependent on the stress conditions.

Besides providing boundary conditions and support for the rock-mechanical analysis, knowledge of the initial in-situ stress distribution indirectly furnishes information on the stability of the rock. High and deviatoric stresses complicate above all the execution of the rock works, since it is in this stage that great changes take place in the stress field around tunnels and deposition holes. Moderate rock stresses in the tunnel periphery have a stabilizing effect. Excessively high or deviatoric tangential stresses in the tunnel periphery in relation to the strength of the intact rock can, however, cause spalling phenomena or contribute to other types of overbreak. The magnitude and direction of the initial stress field thereby directly influences what are suitable tunnel directions and the choice of rock excavation methods.

5.2.2 Requirements and preferences

It is a requirement that extensive spalling phenomena or other extensive rock breakout not occur within the deposition area, since this can make it impossible to construct durable deposition holes (Figure 5-1). This requirement is mitigated outside the deposition area, and here it is also possible to reinforce the rock, which can scarcely be done directly in the deposition holes. Function is verified by a site-specific rock-mechanical analysis, where the resultant stress situation around the tunnels is forecast. The initial stress distribution is included in such an analysis, but it is not possible to directly stipulate requirements on the initial stress distribution.

It is generally an advantage if the initial stresses do not deviate from what is normal in Swedish bedrock (i.e. well below 70 MPa) and are as isotropic as possible at planned repository depth.

5.2.3 Generic knowledge and knowledge obtained at different stages

There is some generic knowledge of the initial rock stress distribution. The vertical stress is as a rule approximately equal to the weight of the overlying rock mass and thereby increases with depth. At a depth of 500 m, the vertical stress is normally about 14 MPa. The greatest horizontal stress at this depth lies in the range 10–70 MPa /Stille and Nord, 1990/.

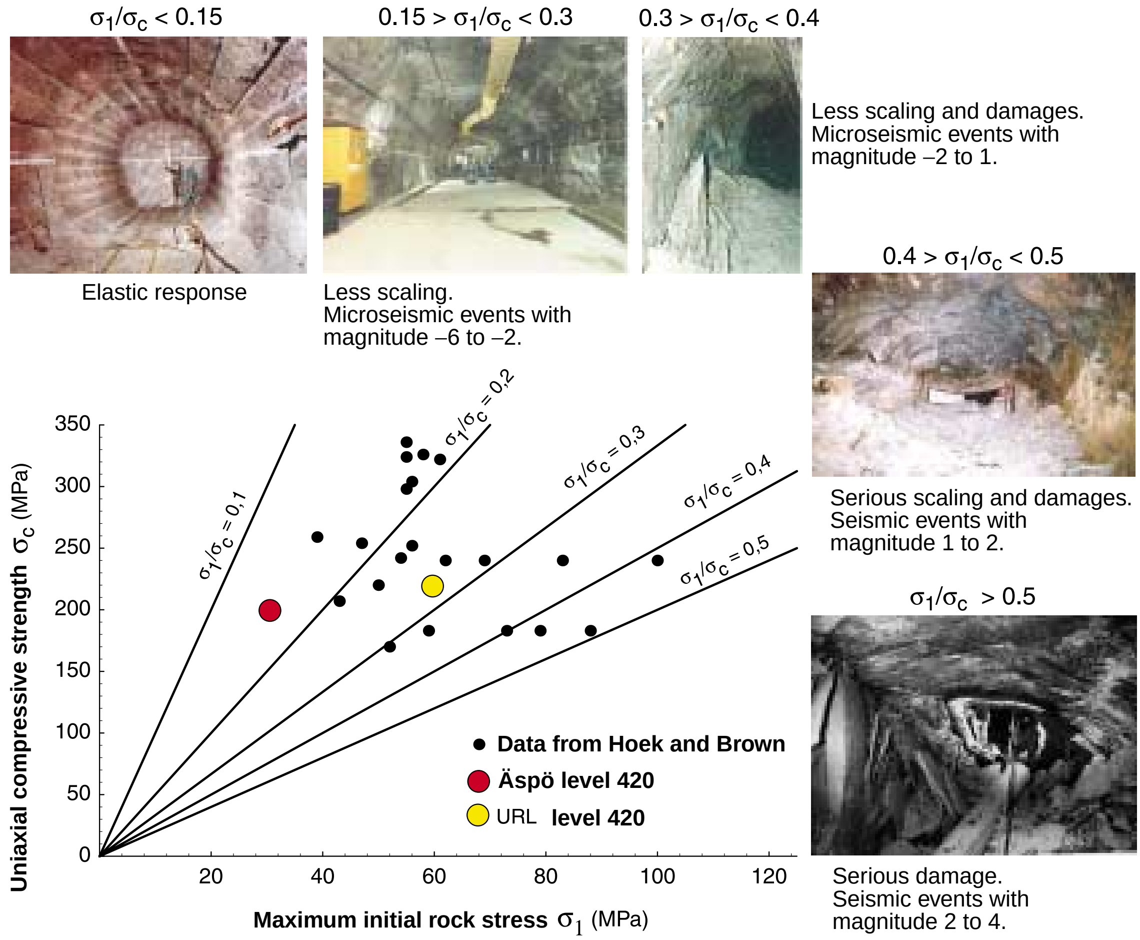

Figure 5-1. *Empirical stability classification developed for mine drifts of rectangular cross-section in South Africa. Modified by /Martin et al., 1999/ from /Hoek and Brown, 1980/. The figure is supplemented with data from the Äspö Hard Rock Laboratory (HRL) and the Underground Research Laboratory (URL) in Canada. It is a requirement that extensive spalling phenomena or other extensive rock breakout do not occur within the deposition area.*

Previous experience from underground projects in the area is collected in feasibility studies. Experience from underground construction (see e.g. the feasibility study in Östhammar /SKB, 1997/) shows, however, that large local variations often occur and that investigations on a specific site with boreholes to the intended depth are necessary so that any local problems will be revealed and reliable construction-related assessments can be made.

In site investigation, the initial stresses can be measured in boreholes by e.g. overcoring and hydraulic fracturing. However, uncertainties and spatial variation are relatively great /Ljunggren et al., 1998/. Additional stress measurements can be made from boreholes at repository level during detailed characterization and repository construction.

5.2.4 Suitability indicators and criteria

Initial rock stresses are obviously useful as suitability indicators, partly for their importance in choice of facility layout and partly because they are included in an analysis of stability conditions during construction and operation.

There are no grounds for issuing criteria based on knowledge from feasibility studies other than the general evaluations that are made within the framework of the feasibility studies.

A qualified site-specific rock-mechanical analysis shall be carried out during the site investigation where the future stress situation in the rock surrounding the tunnels and the resulting rock stability during and after the construction phase are forecast. The input values in the analysis are the tunnel geometry and the estimated (during the site investigation) values and geometric distribution of the strength and deformation properties of the intact rock, the geometry and deformation properties of the fracture system, and the initial rock stresses. Since the function is dependent on many interacting factors, a specific criterion for acceptable initial stresses cannot be set up. Furthermore, the uncertainties in the rock stress measurements have to be taken into account.

If the drill core cracks up into discs ("core discing") it is a strong indication of high stress levels. Extensive problems with core discing should therefore give rise to suspicion that problems may be encountered with spalling during tunnelling.

The analysis is used mainly to adapt siting depth and layout (reinforcements, tunnel geometry, alignements) to prevailing conditions. If the repository cannot be reasonably configured in such a way that extensive and general spalling problems are avoided, the site is unsuitable and should be abandoned.

5.3 Mechanical properties of intact rock

5.3.1 Description of parameters and their influence on functions

By "intact rock" is meant in rock-mechanical contexts rock without visible fractures. As a rule, the deformation properties of the intact rock are described with a linear portion, in the form of the modulus of elasticity (E) and Poisson's ratio (n), and a plastic portion which is dependent on the strength of the material. Further parameters occur in some material models.

The stability of rock-mechanical systems is dependent on the stress conditions. Idealized relationships, failure criteria, give the dependence as a function of the principal stresses. However, the fracturing process in fact starts at lower loads than the actual failure load. Rock in a state of stress equivalent to approximately 80% of the failure load may, without further load increase, be fragmented after some time if the stress level is retained /Martin, 1994/. The phenomenon can be observed at great depth where the primary stresses are high and where rock extraction to create tunnels and other types of cavities gives rise to large stress concentrations. Next to the cavity walls, the tangential stresses are large and the radial constraint small, which can lead to rock breakout due to fracturing parallel to the cavity wall ("splitting failure"). If the splitting failure is violent, a type of rock burst has occurred.

The mechanisms that control the growth of microfractures in principle also control the propagation of existing fractures. In constrained rock, an individual fracture can propagate by spreading in its own plane by means of shear failure, and by fracturing at an angle to its own plane by tensile failure at the periphery of the fracture, so-called "splay cracks" /Scholz 1990/.

For choice of tunnelling methods in conjunction with rock engineering, properties such as penetration index, DRI (drilling rate index), wear properties and blastability need to be determined. These parameters are of no importance from the viewpoints of safety or siting. They are used in the design work for the rock excavation.

5.3.2 Requirements and preferences

See section 5.2.2 for formulation of requirements.

It is a preference that the intact rock should have strength and deformation properties that are normal for Swedish bedrock, since experience has shown that it is possible to carry out the rock excavation works with good results in such bedrock. Furthermore, it is a preference that the strength of the rock should have margin to cope with the stress redistribution that takes place with the chosen tunnel design due to thermal expansion of the rock due to the heat in the deposited canisters.

5.3.3 Generic knowledge and knowledge obtained at different stages

There is good generic knowledge of the mechanical properties of the intact rock /Stille and Nord, 1990/. As a rule, the intact rock in Swedish crystalline basement has a modulus of elasticity between 5 and 100 GPa, a Poisson's ratio between 0.15 and 0.30, a compressive strength between 50 and 250 MPa and a tensile strength between 2 and 10 MPa.

The feasibility study's assessment of which rock types occur furnishes additional information, since strength varies with different rock types. Site-specific information can be obtained from mapping, classification and tests on drill cores retrieved in conjunction with site investigation. The detailed characterization furnishes more direct knowledge on the intact rock located close to tunnels and deposition holes.

The parameters blastability, penetration index, DRI and wear properties are used generally in the construction analysis to estimate construction costs, as well as in the detailed engineering stage. None of these parameters influence the choice of site.

5.3.4 Suitability indicators and criteria

The compressive strength of the intact rock is a useful suitability indicator, but cannot be used in isolation to judge the risk of extensive spalling or other extensive overbreaks.

The rock type assessment that can be made during a feasibility study furnishes a general basis for determining the strength and deformation properties of the intact rock. The difference in properties between the rock types that are suitable for hosting a deep repository is, however, relatively limited. For criteria during site investigation, see section 5.2.4.

5.4 Fractures and fracture zones

5.4.1 Description of parameters and their influence on functions

The occurrence of fractures and fracture zones is of great importance for the mechanical properties of the rock. Compared with the rock without visible fractures, the strength and stiffness of the fractures is small in the plane of the fractures and the zones. Moreover, the fractures and fracture zones have negligible tensile strength perpendicular to the fracture plan. Stiffness against displacements in the plane of the fracture/zone limits its persistence. Large (persistent) fracture zones have greater prospects of being displaced than small ones.

Fractures can be deformed perpendicularly to the plane of the fracture (normal deformation) or in the plane of the fracture (shear deformation). If the stress varies perpendicularly to the plane of the fracture, the fracture may open or close. The relationship between normal stress and normal deformation is usually described by normal stiffness /see e.g. Barton et al., 1985/. Fractures can also be deformed in the plane of the fracture – shear movements. Shear failure occurs when the load is too high. The shear strength of the fracture is dependent on, among other things, the size of the normal stress across the fracture (friction). If the ratio between shear load and normal stress exceeds a given value (the "friction angle"), friction is not sufficient to prevent a movement. The size of the movement is, however, also determined by the size of the fracture /Turcotte, 1992/. Deformation is small for short fractures, even if friction is neglected.

Normal deformations lead to a change in fracture aperture. This also changes the permeability of the fracture. Shearing along non-planar fractures can cause aperture variations due to the roughness and waviness of the fracture. This also leads in turn to changes in the permeability of the fracture. This hydromechanical coupling is, however, of relatively limited importance for long-term safety, although it may need to be taken into account in the evaluation of hydraulic tests (e.g. /Rutqvist et al., 1996/).

The deformation properties of the individual fracture are of some importance for assessing the mechanical stability in a rock cavern. It is generally an advantage if the fractures have a high friction angle, since this further increases rock stability. Stability is determined essentially by arch formation, the risk of overbreak wedges, and the occurrence of rock bridges of intact rock. For the mechanical assessment it is chiefly the geometry (direction) of the tunnel and the geometry (direction) of the fractures in relation to directions of stress fields and future changes in them that are of importance, but high friction in the fractures contributes to increased stability.

5.4.2 Requirements and preferences

In order to ensure that the deposition holes are not deformed in a manner that could damage the canister, it is a requirement that deposition holes not be allowed in or near regional or local major fracture zones (see further discussion in section 4.6).

The geometry of local minor fracture zones and individual fractures is also of great importance for whether the deposition holes can be deformed. Individual deposition holes are not to be positioned so that they intersect minor fracture zones. The individual fractures are also of importance, but the function analyses with a mechanical model that have been done within the framework of the SKI project SITE-94 /Hanson et al., 1995/ could not find any case where the deformation of the deposition hole exceeded 0.1 m. The adaptation of the repository layout to the geometry of the fracture network is of direct importance for the impact of seismic events, see /LaPointe et al., 1999/. However, it is not possible to stipulate requirements or preferences regarding the geometry of fractures or fracture zones; instead, the resulting function needs to be analyzed.

There are no grounds for stipulating exact requirements or preferences regarding how the deformation properties of the fractures influence permeability.

From a rock excavation point of view, a suitable positioning, layout and reinforcement of tunnels is chosen on the basis of prevailing fracture frequency, fracture geometry and rock stresses. Fracture geometry and fracture angles should also be such that the quantity of overbreak in the deposition holes (see section 5.1.3) is not too great. However, it is not possible to stipulate more exact preferences regarding geometry here either; instead, an assessment must be made from case to case. From the viewpoint of stability during construction, it is also desirable that the friction angle of the fractures not be too small. A high friction angle is also advantageous for long-term safety, but the friction angle is not decisive for the mechanical stability of the repository.

5.4.3 Generic knowledge and knowledge obtained at different stages

See section 4.6 regarding the geometry of fractures and fracture zones. There is good generic knowledge of the mechanical properties of fractures /Stille and Nord, 1990/.

A feasibility study does not in itself furnish any new information. Site-specific information can be obtained by performing laboratory tests on fractures in drill cores retrieved in conjunction with site investigation. In view of the limited importance of the information, however, a large number of measurements are not needed. Detailed characterization provides more direct knowledge on the individual fractures located close to tunnels and deposition holes.

5.4.4 Suitability indicators and criteria

The occurrence and geometry of fracture zones are obviously useful as suitability indicators from a rock-mechanical viewpoint as well. In order to be able to judge whether requirements or preferences are satisfied for a given fracture geometry, however, it is as a rule necessary to carry out a specific mechanical analysis to assess the risk of block breakout. However, such an analysis can, in simple cases, be carried out with geometric information alone. Criteria for adaptation of the repository to known fracture zones are discussed in section 4.6.4.

It is not meaningful to carry out a quantitative rock-mechanical analysis with the information that is available after a feasibility study. After a site investigation, the location of most regional and local major fracture zones should be known. If their frequency is so high that the repository cannot be positioned without being split up into a very large number of parts, the site is unsuitable.

Mechanical properties of fractures particularly need to be assessed for detailed characterization and repository construction. The mechanical properties of the fractures are therefore less useful as suitability indicators, even though it is preferable that fractures with extremely low friction not occur within the repository area.

The laboratory tests on drill cores that can be done during a site investigation reveal properties on a centimetre scale. These values are needed to build up the geoscientific understanding of the site and can furthermore be used in the construction analysis (e.g. for assessment of reinforcing needs). Conservative assumptions (frictionless and cohesionless fractures) are as a rule made in the safety assessment. Owing to the small importance of the preferences and the large measurement problems, there is no reason to stipulate criteria, not even during the site investigation.

5.5 Mechanical properties of the rock mass as a whole

5.5.1 Description of parameters and their influence on functions

In connection with practical rock-mechanical modelling of stability on a repository scale, only the major fracture zones are modelled explicitly, and then as a rule as zones with deviant strength properties. The rock, both in fracture zones and in between, is denoted by the term "rock mass", which represents the strength properties for the non-explicitly-described fractures and the intact rock together.

The concept of rock mass must be related to the scale on which the rock is described. In the rock-mechanical analysis normally carried out by SKB, regional and local major fracture zones are described explicitly and are therefore not included in the rock mass. In more detailed discrete analyses, local minor and individual fractures can also be described explicitly, albeit stochastically. The intervening rock corresponds to "intact rock" in this latter case.

It is not customary to stipulate values of the strength of the rock mass. If failure occurs in the rock mass, it occurs in most cases due to a complex combination of failure in the intact rock and deformation/failure in the fractures. An exact description of the failure process is seldom possible; instead, empirical failure criteria and classifications of the rock mass, such as the Q system /Barton, 1974/ or the RMR system (see e.g. /Brady and Brown, 1993/), are normally used to determine if there is a risk of problems. The empirical classification methods can be used as a basis for designing rock support /National Road Administration (1999)/, but are open to criticism for providing a oversimplified picture of complex processes and relationships. Empirical classifications can be used as tools in the ongoing design work, but constructability is verified by means of rock-mechanical analyses.

5.5.2 Requirements and preferences

It is not meaningful to stipulate requirements on the rock mass.

From the constructability viewpoint in particular, there are preferences that the rock mass – which includes local minor fracture zones, individual fractures and the intact rock – should have a strength that is at least on a par with normal conditions in Swedish bedrock.

5.5.3 Generic knowledge and knowledge obtained at different stages

There is good generic knowledge of the mechanical properties of the rock mass.

Previous experience from underground projects in the area is collected in feasibility studies. Experience from underground construction (see e.g. the feasibility study in Östhammar /SKB, 1997/) shows, however, that large local variations often occur and that borehole investigations on a specific site to the intended depth are necessary so that any local problems will be revealed and reliable construction-related assessments can be made.

Site-specific information on the properties of the rock mass can be obtained by logging and classification of drill cores retrieved in conjunction with site investigation. The detailed characterization furnishes more knowledge, above all the direct experience gained from building in the rock in question.

5.5.4 Suitability indicators and criteria

In view of the above preferences, the strength of the rock mass is a useful suitability indicator. The requirement on precision in the determination is, however, limited, and in analyses based on site investigation data, sensitivity analyses for known extreme values will primarily be carried out.

There are no grounds for issuing criteria based on knowledge from feasibility studies other than the general evaluations that are already made within the framework of the feasibility studies.

The forecast of the properties of the rock mass that is made in conjunction with the site investigation is utilized for repository layout and for the constructability forecast. The constructability forecast is included in the total comparison material between sites, but has no direct safety-related importance. Good constructability is of course advantageous.

5.6 Coefficient of thermal expansion

5.6.1 Description of parameter and its influence on functions

The coefficient of thermal expansion is a measure of the change in volume of the rock due to a change in temperature. The coefficient of thermal expansion, together with heat transport data (thermal conductivity and specific heat), comprises model data in calculation of the stress changes and deformations that occur due to thermal load. Since the rock in the repository is constrained, the expansion is completely or partially suppressed, and thermal stresses are generated in the rock mass surrounding the deposition holes and the repository. The size of the volume expansion and the thermal stresses is dependent on the coefficient of thermal expansion and the deformation properties of the rock.

Due to heat production in the repository, special attention must be given to the threat that tensile stresses might arise at great depth. Around individual deposition holes, it is important that thermal expansion be sufficiently even.

The coefficient of thermal expansion is dependent on the mineral composition of the rock, although the variations between different rock types are not great. Initial analyses have been made by Hökmark (1996).

The thermal displacements as such have no direct bearing on safety. However, the thermal load contribution can, together with the loads that already exist in the initial state, cause the strength of intact rock and fractures to be exceeded. This needs to be checked in a site-specific function analysis, but does not entail direct requirements or preferences regarding the coefficient of thermal expansion.

5.6.2 Requirements and preferences

There is no reason to make requirements on the coefficient of thermal expansion within the range of variation that is possible in a crystalline bedrock.

It is preferable that the parameters have normal values for Swedish bedrock (within the range 10^{-6} to 10^{-5} K^{-1}) and that they do not differ much between the rock types that exist in the repository area.

5.6.3 Generic knowledge and knowledge obtained at different stages

The probable value range for the coefficient of thermal expansion in Swedish crystalline bedrock is between $3 \cdot 10^{-6}$ K^{-1} and $1.5 \cdot 10^{-5}$ K^{-1}.

There is good generic knowledge of the value of the coefficient of thermal expansion. A feasibility study can provide some idea of which types of rock occur at depth. But it is not until the site investigations that samples of drill cores obtained during the site investigations can provide a more accurate picture of the rock type distribution within the repository area. The detailed characterization provides more direct knowledge in areas located close to tunnels and deposition holes.

5.6.4 Suitability indicators and criteria

The coefficient of thermal expansion is not a primary suitability indicator, but needs to be determined during a site investigation. The coefficient is necessary to know for a thermomechanical analysis, but values within the above value ranges can be used. Any preferences on a deposition hole scale can be handled during repository construction and in connection with the selection of deposition holes.

A rough mineralogical description is obtained during the feasibility study, but rock type inhomogeneities can only be judged in general terms from the surface characterization. Highly inhomogeneous conditions on the surface do, however, warrant more thorough characterization during the site investigation.

The more detailed knowledge obtained from drill cores during a site investigation does not provide grounds for quantitative criteria either. If the rock is very heterogeneous, more extensive investigations are required. A thermomechanical analysis needs to be done in any case, but its results are dependent more on fracture geometry and initial stress conditions.

5.7 Future loads

5.7.1 Description of parameters and their influence on functions

Future external events could affect the mechanical stability of the rock. The effects of earthquakes and future ice ages in particular were studied in SR 97 /1999a/.

Seismic activity during the next 100,000 years was estimated in the seismic analysis carried out within the framework of SR 97 /La Pointe et al., 1999/ by extrapolating from present-day seismic activity. This estimate (frequency and magnitude) is included directly in the analysis. According to the analysis, only earthquakes with a magnitude greater than about 7 that occur in fracture zones in the immediate vicinity of the repository can cause deformations large enough to damage the canister. Such large earthquakes can, on the other hand, only occur in regional fracture zones, which will be avoided in locating the repository. Furthermore, the analysis exaggerates the consequences, since it is assumed that the shear deformation of the fractures is not hindered by friction in the plane of the fracture. In other words, the analysis is based on several pessimistic assumptions.

In the analysis of a glaciation scenario, the mechanical effects of the ice sheet are studied. No fracture movements large enough to damage canisters have been obtained for the load cases analyzed so far in numerical models /e.g. Hansson et al., 1995/. For other reasonable static load cases as well, the judgement can be made that no shear movements in fractures intersecting canister hole positions will be large enough to damage the canister (see SR 97, Main Report, Chapter 10 /SKB, 1999a/).

5.7.2 Requirements and preferences

It is obviously advantageous if future seismic activity is of low magnitude and occurs at low frequency. The regional differences that exist in different forecasts are, however, too small in relation to the uncertainties. Both ice age and earthquakes belong to scenarios that are analyzed within the framework of a safety assessment, but the analyses have little coupling to the choice of site. Because the layout of the repository is adapted by not allowing deposition holes to intersect local minor fracture zones (see 5.4), the risk of earthquake-induced damage is also minimized.

5.7.3 Usefulness as suitability indicators

The forecasts of future earthquakes and ice ages and analysis of the consequences if they occur must be done within the framework of a safety assessment. The safety assessment SR 97 /SKB, 1999a/ is based on pessimistic assessments of the scope of these events. In view of the uncertainties, however, it is not reasonable to use forecasts of future seismic activity or forecasts of future ice ages as suitability indicators.

5.8 Summary suitability indicators – rock mechanics

The preceding sections have provided an account of which rock-mechanical suitability indicators may be relevant in different stages of the siting work. A complete account of this work can be found in Table A-2 in Appendix A and Table B-2 in Appendix B.

As is evident above, suitability indicators are mainly used to assess whether requirements and preferences are satisfied. Table 5-1 provides a compilation of the suitability indicators that have been preliminarily identified for rock mechanics.

Table 5-1. Suitability indicators for rock mechanics (the complete account is found in Appendices A and B).

Parameters – groupwise	Requirements or preferences	Criteria during feasibility study (FS) and during site investigation (SI)
Initial rock stresses	Extensive spalling or other extensive overbreak may not occur within a large portion of the deposition area. Function is verified by means of a site-specific analysis. Preference for normal (considerably lower than 70 MPa) initial stresses at repository depth.	FS: No criteria SI: Calculated stress situation in the rock nearest the tunnels and the resultant rock stability during and after the construction phase is used mainly to adapt repository depth and layout. If the repository cannot be reasonably configured in such a way that extensive and general spalling problems can be avoided, the site is unsuitable and should be abandoned. Extensive problems with "core discing" should directly give rise to the suspicion that problems may be encountered with spalling during tunnelling.
Intact rock (E, ν, compressive strength etc.)	Extensive spalling or other extensive rock breakout may not occur within a large portion of the deposition area. It is preferable that the intact rock have strength and deformation properties that are normal for Swedish bedrock.	FS: Assessment based on preliminary rock type forecast may not indicate unfavourable conditions. SI: Special attention if the strength of the rocks deviates strongly from normal values in Swedish bedrock. See also "initial rock stresses".
Fractures and fracture zones	For adaptation to geometry of fracture zones and fractures – see "geology". Tunnel layout/location is chosen based on stresses and fracture directions. Large friction angle suitable.	FS: For adaptation to geometry of fracture zones and fractures – see "geology". SI: For adaptation to geometry of fracture zones and fractures – see "geology". Rock-mechanical analysis of function (see "intact rock" above.)
Rock mass as a whole	No requirements Properties at least on a par with normal conditions in Swedish bedrock.	FS: No criteria SI: The forecast of the properties of the rock mass that is made in conjunction with the site investigation is used for repository layout and the constructability forecast. The constructability forecast is included in the total comparison material between sites, but is of no direct safety-related importance. Good constructability is of course advantageous.
Coefficient of thermal expansion	No requirements Normal and homogeneous properties preferable.	No criteria during FS and SI, but attention to heterogeneous conditions. Any problems with rock type boundaries are handled during detailed characterization and repository construction.
Future loads	No requirements	No grounds for comparisons or criteria in view of uncertainties in forecasts.

6 Temperature

6.1 Thermal properties that influence the function of the deep repository

The thermal properties of the rock can above all influence the isolating function of the deep repository. However, safety requirements can always be met by means of a suitable layout of the repository. From the construction viewpoint, but also indirectly from the safety viewpoint, there is therefore a preference that the repository should not be too spread out. The necessary size of the repository area is influenced by the thermal properties of the rock. Appendix A-3 summarizes how the thermal properties influence functions and what requirements and preferences can be derived from this. The thermal evolution of the deep repository, as well as the consequences of this evolution for the functions of the deep repository, are analyzed thoroughly in SR 97, Main Report, section 8.6 /SKB, 1999a/.

6.1.1 Influence on canister integrity

It is a requirement that the maximum temperature on the canister surface shall be lower than 100°C /Werme, 1998/. It is not good if the water boils so that salt deposits form which could later dissolve and make the groundwater more aggressive. (After closure, however, the pressure, and thereby also the boiling point, of the groundwater will increase considerably.)

The temperature is determined by the decay heat of the spent fuel, the repository layout, the thermal conductivity, heat capacity and initial temperature of the rock, and the water saturation of the bentonite. The repository layout is determined so that the temperature requirement is satisfied (see also the Base Scenario in SR 97, Main Report /SKB, 1999a/). No requirements can therefore be made on the thermal properties of the rock. However, it is preferable that the repository not be too spread out, since this leads to a more expensive repository and could make the site investigation more difficult and increase the risk that other undesirable properties in the rock are not detected.

6.1.2 Influence on the isolating and retarding capacity of the buffer

For the same reasons as for the canister, it is a requirement that the highest temperature in the buffer is lower than 100°C. Higher temperatures in combination with unsuitable water chemistry could influence the stability of the bentonite. However, this requirement is automatically satisfied if the canister requirement is met. The possibility cannot be ruled out that an insulating air gap arises between canister and bentonite /Bjurström, 1997/. The influence of this gap was handled in /SKB, 1999a/ by assuming a temperature drop of 10°C between buffer and canister, and in addition a safety margin of 10 degrees was assumed to manage uncertainties in various data /Ageskog and Jansson, 1999/. The maximum permissible temperature at the buffer's inner boundary was thereby 80°C. This requirement can always be met by means of a suitable repository layout (see also 6.1.1).

6.1.3 Influence on the isolating and retarding capacity of the rock

Thermomechanical requirements and preferences regarding the rock are discussed in the chapter on rock mechanics, section 5.1.

To guarantee the isolating capacity of the rock, it is preferable that the site should not have particularly suitable prospects for extraction and storage of geothermal energy (competing interests). This question is discussed in General Siting Study 95, and a preliminary conclusion is that this preference is satisfied by means of the suitability indicators already applied in the feasibility studies.

To simplify the hydrogeological analysis, it is desirable that thermal convection not be a considerable driving force for groundwater flow, relative to other driving forces. As a rule, the thermal driving force is negligible compared with the topographical one (see e.g. Thunvik and Braester, 1980). From a hydrogeological viewpoint, there are therefore no reasons for requirement or preferences regarding the thermal properties of the rock.

6.1.4 Biosphere-related matters

The decay heat from the repository must not cause a noticeable temperature increase at the ground surface. Such an increase could affect the ecosystems. However, the analysis of the base scenario in SR 97 (Main Report, section 8.6.2 /SKB, 1999a/) shows that the heat from the repository will only have an extremely marginal influence (equivalent to approximately 0.1% of the influence of solar radiation) on the thermal conditions on the ground surface, so that this preference will always be satisfied.

6.1.5 Construction-related matters

The layout of the deep repository is subject to an economic preference that each canister should hold as much fuel as possible. The layout must also satisfy the above temperature requirements and preferences. This is in principle always possible to do, but the resultant temperature distribution for a given layout must be analyzed by thermal analysis in order to check the temperature functions. Since there are also other factors (mainly occurrence of regional and local major fracture zones) that govern the configuration of the repository, it is not certain that the temperature requirements will ultimately determine the extent of the repository.

6.2 Parameters that describe heat transport

6.2.1 Description of parameters and their influence on functions

Heat transport through the rock takes place primarily by heat conduction, which is determined by the heat capacity and thermal conductivity of the rock. (Heat transport by radiation and convection can be neglected.) The heat transport through the rock influences the temperature in the different barriers. Temperature changes also influence the volume of the rock, which is determined by the coefficient of thermal expansion. This parameter has already been discussed in the chapter on rock mechanics, section 5.6.

It is a requirement that the temperature on the surface of the canister be less than 100ºC. If this requirement is met, the temperature will not exceed 100ºC in any of the barriers either. This requirement can always be satisfied by adjusting the quantity of fuel in the canister or by adapting the repository layout, for example by adjusting the distance between deposition holes, provided the thermal properties of the rock and ambient temperatures (see below) are known. Good heat conduction and high heat capacity are prerequisites for a more densely packed repository.

6.2.2 Requirements and preferences

There are no requirements regarding the thermal properties of the rock, since applicable functional requirements can always be satisfied by a suitable repository layout.

There is a preference for high thermal conductivity, i.e. $\lambda > 2.5$ W(mK)$^{-1}$ (Figure 6-1). At lower thermal conductivity, the spacing between the deposition holes in the KBS-3 design must increase or the amount of fuel in each canister must decrease. It is also good if the rock has homogeneous thermal properties. These preferences are mainly economical, since a more spread-out repository is more costly. Indirectly, however, the preferences have some bearing on safety since it can be more difficult to characterize a very extensive and complex repository area in a good way. The size of the repository area will, however, more probably be determined by existing fracture zones. As a rule, Swedish crystalline rock satisfies the expressed preferences.

6.2.3 Generic knowledge and knowledge obtained at different stages

Typical value ranges for the thermal properties of the crystalline bedrock in the Fennoscandian Shield have been compiled on the basis of a modified rock type grouping in accordance with the Swedish National Atlas and a statistical processing of thermal properties based on mineral compositions according to the Geological Survey of Sweden /Sundberg, 1995 and Sundberg, 1998/. Good correlations between values based on modal analysis (mineral composition) and heat conduction measurement in the field have been obtained in earlier studies /Ericsson, 1985 and Sundberg, 1988/. Difference in mineral composition leads to different thermal conductivities in different rock types. Quartz has a thermal conductivity of 7.7 W(mK)$^{-1}$, which is 3–4 times higher than for other minerals. The quartz content of a rock is therefore crucial for its heat conduction.

A simplified grouping of mean values and ranges for different rock types gives the following results: Basic rock types (porphyrites, basic volcanites, dolerite, gabbro, diorite, amphibolite, etc.) have a mean value of 2.5 W(mK)$^{-1}$, and the values usually fall in the interval 1.7–3.6 W(mK)$^{-1}$. Rock types of intermediate composition (granodiorites, certain gneisses, certain volcanites) have a mean value of 3.2 W(mK)$^{-1}$ and values usually fall in the interval 2.2–4.2 W(mK)$^{-1}$. Quartz-rich rocks (granites, acid gneisses, quartzites, acid volcanites, etc.) have a mean value of 3.6 W(mK)$^{-1}$, with a typical value range of 2.5–5.5 W(mK)$^{-1}$.

The thermal properties are determined primarily on the basis of knowledge of rock type composition. As mentioned previously (see section 4.4), knowledge of the main rock types in the superficial bedrock is usually good during a feasibility study. Detailed knowledge of rock type distribution is obtained during the site investigations.

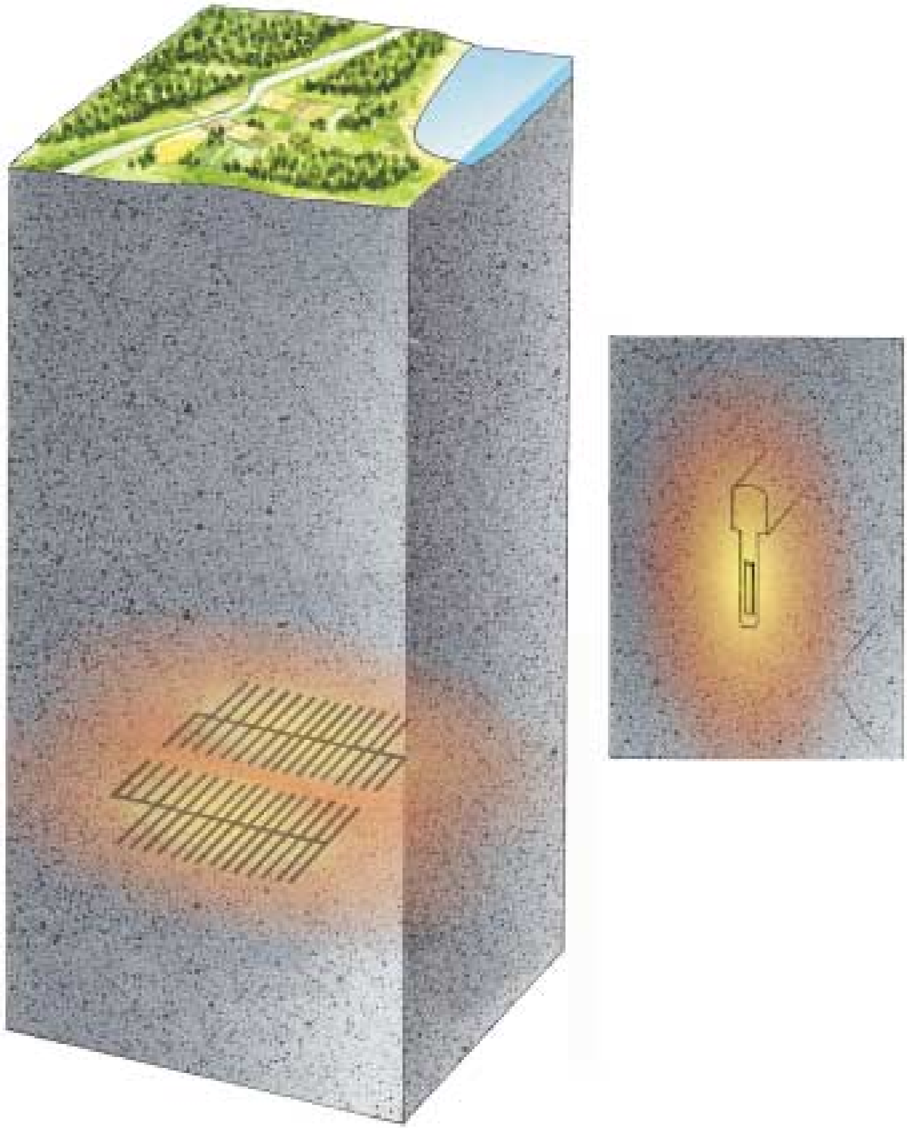

Figure 6-1. *It is good if the rock has a thermal conductivity higher than 2.5 W/(mK).*

6.2.4 Suitability indicators and criteria

Parameters for heat transport should be included as suitability indicators, since the layout of the repository is in part determined by these parameters. The functional requirements can however always be met with ample safety by means of a suitable repository layout. The parameters could be of some importance for comparison between the sites, since having a small repository area (and thereby a small area that needs to be thoroughly investigated) can be economically advantageous. On the other hand, there are other factors (e.g. frequency of fracture zones) that also influence the size of the area that needs to be studied and used. Moreover, the deposition holes cannot be spaced too closely, for strength reasons among others. It is therefore no further advantage if the thermal conductivity is much higher than the stated preference of 2.5 $W(mK)^{-1}$.

During a feasibility study, knowledge exists of which rock types exist in areas of interest, and an estimate can be made of the expected temperature at repository depth. This enables the size of the repository as determined by heat considerations to be calculated.

In practice, however, the heat parameters vary little within rock types such as granite and gneiss, so that differences in these parameters will presumably be of little importance for what areas are chosen for site investigation. It is only if thermal conductivity is judged to be less than preferred that the size of the area that must be studied is affected.

During the site investigation, good knowledge exists of rock composition and heat conduction properties, which is used to adapt the repository layout. However, thermal conductivity only influences the size of the repository if there is a risk that it will be less than preferred.

6.3 Ambient temperatures

6.3.1 Description of parameters and their influence on functions

The temperature distribution in the rock is determined by the transport parameters discussed in preceding sections and by the initial temperature of the rock and groundwater (initial condition), which is chiefly determined by the annual mean temperature on the surface and the geothermal gradient.

Functional requirements and preferences for the temperature distribution can always be satisfied by adapting the repository design and layout (e.g. quantity of fuel in canister, spacing between deposition holes or siting depth), provided the thermal properties of the rock and ambient temperatures are known. It is, however, an advantage if the initial temperature at repository depth is not so great that it significantly affects the spacing between deposition holes and tunnels.

Areas with large potential for geothermal energy extraction (very high geothermal gradient) should be avoided from a natural resource point of view. However, such areas do not exist in the Swedish bedrock.

6.3.2 Requirements and preferences

There are no requirements on ambient temperatures, except that areas with a large potential for geothermal energy extraction (very high geothermal gradient) should be avoided.

In order to keep the repository to a reasonable size, a preference is that the initial temperature at repository depth should be less than 25°C. However, this preference is only formulated from an economic perspective.

6.3.3 Generic knowledge and knowledge obtained at different stages

The initial temperature at 500 m depth lies between 7°C (northern Sweden) and 18°C (southern Sweden). The thermal gradient lies between 10°C/km and 15°C/km /Sundberg, 1995/.

The initial temperature distribution in the rock is determined primarily by the geographic situation of the site, which means that good knowledge of this can be obtained already during feasibility studies. Any anomalies can be revealed from boreholes in conjunction with site investigations.

6.3.4 Suitability indicators and criteria

The initial temperature at repository depth should be included as a suitability indicator, since the design and layout of the repository is partially determined by this parameter. The functional requirements can however always be met with ample safety by means of a suitable repository layout. The initial temperature could be of some importance for comparison between sites, however, since having a small repository area (and thereby a small area that needs to be thoroughly investigated) can be economically advantageous. However, the temperature is of little importance for comparison between sites if it is judged to lie below the preferred level (25°C). There are other factors (e.g. strength, frequency of fracture zones, etc.) that have a greater influence on how large an area needs to be studied and used. Data for a more detailed repository layout are available during the site investigation.

6.4 Summary suitability indicators – temperature

The preceding sections have provided an account of which suitability indicators may be relevant in different stages of the siting work. The complete account of the work is found in Tables A-3 in Appendix A and B-3 in Appendix B.

As is evident from the above, suitability indicators are mainly used to determine whether requirements and preferences are satisfied. Table 6-1 provides a compilation of the suitability indicators that have been preliminarily identified for thermal properties.

Table 6-1. Suitability indicators for thermal properties (the complete account is found in Appendices A and B).

Parameters – groupwise	Requirements or preferences	Criteria during feasibility study (FS) and during site investigation (SI)
Heat transport conductivity and heat capacity)	No requirements Preference regarding good thermal conductivity (influences repository layout, repository size) i.e. λ>2.5 $Wm^{-1}K^{-1}$.	FS: If an assessment is made (from rock (thermal types) that thermal conductivity is below the preferred value, the size of the area that must be studied is affected. SI: Detailed knowledge of rock types and thermal conductivity is used to adapt the repository layout. However, Thermal conductivity only has to be taken into account if there is a risk that it is below the preferred level (2.5 $Wm^{-1}K^{-1}$).
Ambient temperature (initial, external temperature and thermal gradient).	Areas with potential for geothermal energy extraction (very high geothermal gradient) should be avoided. Preference that initial temperature at repository level <25°C.	FS: Avoid areas with assessed large potential for geothermal energy extraction. If the initial temperature is judged to exceed the maximum preferred, it must be taken into account in the choice of how large an area needs to be investigated. SI: Like FS. The repository layout must take into consideration the initial temperature if it is above or near the maximum preferred.

7 Hydrogeology

7.1 Influence on the function of the deep repository

The groundwater flow through the rock influences both the isolating and retarding functions of the deep repository. A review of the functions that are influenced by the groundwater flow reveals that it is mainly the permeability of the rock that influences the functions, see Appendix A-4. Requirements and preferences regarding parameters associated with hydrogeology are discussed in detail in the following sections.

7.1.1 Influence on canister integrity

To guarantee a suitable chemical environment for the canister, groundwater of unsuitable composition should not be able to flow to the repository area for any extended period of time.

There is in principle a preference for low groundwater flow on a deposition hole scale in order to limit the influx of substances that could corrode the copper canister, but calculations show (e.g. SR 97 base scenario /SKB 1999/) that the flow does not play any significant role if the sulphide content of the water lies within the values that have been measured in deep groundwaters in Sweden and Finland (see section 8.2.3).

The canister's ability to withstand hydrostatic pressures is site-independent. The canister is designed to withstand, with a good margin of safety, an external load composed of the hydrostatic pressure and the bentonite's swelling pressure /Werme, 1998/. The analysis in SR 97 furthermore shows that the canisters can withstand the higher pressures that arise during a glaciation (SR 97, Main Report /SKB, 1999a/).

7.1.2 Influence on the isolating capacity of the buffer

The groundwater flow in the near zone influences the wetting and swelling of the buffer. Very uneven wetting can influence the swelling pressure around the canister during the wetting process. The water content of the buffer also influences its thermal conductivity. After water saturation, an even swelling pressure arises. Maintenance of water saturation and swelling pressure are a prerequisite for the buffer to act as a diffusion barrier.

It is a requirement that swelling of the bentonite take place so that the canister is not damaged. An uneven influx of water to the deposition hole may cause the bentonite to swell unevenly, and the question has been raised whether this could pose a threat to the canister. In previously performed simple handbook calculations /Werme, 1998/, a number of hypothetical cases of uneven swelling were analyzed. The calculations did not take into account the bentonite's inherent capacity to absorb deformations and thereby exaggerated the importance of the uneven swelling. As a rule, however, these simple calculations show that the resultant stresses are lower than the strength of the canister. In some cases, though, more advanced calculations are needed to check whether there is a risk of canister damage. FEM calculations were carried out within SR 97 where the material properties of the bentonite were also taken into account to arrive at a more realistic load on the canister /Börgesson and Hernelind, 1998/. The largest tensile stresses in the canister insert were then found to lie below 55 MPa, which is far below the yield strength of the cast iron insert. This means that there are no grounds for making requirements on even flows in the deposition hole.

There is a preference for a sufficient influx of water from the rock so that the buffer is saturated quickly enough and so that its thermal conductivity is sufficiently high. Function analyses of swelling and interaction with the groundwater flow in the rock were carried out in SR 97 (SR 97 Main Report, Chapter 8 /SKB, 1999a/ and /Börgesson and Hernelind, 1998/).

The preference for low flows to achieve high retardation of radionuclide transport (see section 7.1.3) is somewhat in conflict with the preference for a sufficient influx of water for swelling of the bentonite. The question is being studied in the ongoing "prototype repository project" at the Äspö HRL (see e.g. /Hermanson et al., 1999/). In the unlikely event that problems should be encountered achieving sufficient water saturation in the event of excessively dry deposition holes, this can be solved by means of various engineering measures. The preference for low flows to achieve good retardation is thereby stronger than the preference for a sufficient influx of water for saturation of the bentonite.

7.1.3 Influence on the retarding capacity of the geosphere

It is preferable that the transport of radionuclides be retarded at the buffer/rock and tunnel/rock transition. Retardation is great at low groundwater flows and few fractures with a small aperture where they intersect the deposition holes /Moreno and Gylling, 1998/. Calculations in SR 97 (Main Report, canister defect scenario /SKB, 1999a/) shows that if the groundwater flow ("Darcy velocity") for the fractures that intersect the deposition hole is greater than $q_{max} = 0.01$ m/y, the retardation at the buffer/rock transition is virtually negligible (see section 9.2). Lower flows are of course preferable, but there are no grounds for a requirement, since the calculations also show that the radionuclide release to the biosphere can be kept below levels set in SSI's regulations /SSI, 1998/ even if the retardation at the buffer/rock transition is neglected.

The groundwater flow between a damaged canister and the biosphere is an important factor for how much radionuclides are retarded in the rock itself /Andersson et al., 1998b/. Calculations in SR 97 (Main Report, section 9.11 /SKB, 1999a/) show that retardation in the geosphere is considerable for transport pathways that have a "transport resistance" (or F parameter) greater than 10^4 m/y (see section 9.3). Large transport resistances in the geosphere are of course preferable, but it is not possible to stipulate a more precise requirement than that the overall barrier function should offer adequate safety. Radionuclide release to the biosphere can be kept below levels set in SSI's regulations /SSI, 1998/ even if not all transport pathways from repository to biosphere have a high transport resistance.

7.1.4 Biosphere-related matters

There are no requirements on near-surface conditions. From a natural resource viewpoint, it is preferable to avoid areas that are (or may be) important water sources, soil sources or farmland. Thick, water-bearing soil strata complicate investigations from a constructional and operational viewpoint. From a natural resource viewpoint, requirements/preferences exist to avoid areas where biological diversity or species worth protecting may be threatened directly or indirectly by construction of access roads and the like in virgin areas.

Data on the near-surface ecosystems are primarily valuable for building up a credible model description. In other words, good access to such data of high quality increases the credibility of the modelling and reduces the uncertainty of the results.

Furthermore, the impact on the superficial groundwater (lowering of the groundwater table and chemical changes) must be minimized. This entails preferences for limited seepage of groundwater into the repository during construction and operation. This preference can be satisfied by means of a suitable layout of the repository, choice of grouting methods and a suitable choice of methods for building the repository (see 7.1.5).

7.1.5 Construction-related matters

There are a number of hydrogeological conditions that must be taken into account in the configuration and construction of the deep repository.

- A preference is that water seepage be moderate or that areas with too much seepage can be sealed with reasonable grouting measures (grouting need), since this affects costs and building times.
- Grouting must be carried out so that there is no risk of serious environmental impact or a negative impact on the composition of the groundwater in the deep repository.
- From an occupational safety viewpoint as well, the probability of heavy water seepage/cave-in must be low, but problems can always be managed with increased costs as a consequence.

The repository is configured so that groundwater flow in the repository area is low by avoiding regional and local major fracture zones in the deposition tunnels.

7.2 Permeability

7.2.1 Description of parameters and their influence on functions

The magnitude of the groundwater flow and its distribution in the rock are primarily determined by the permeability of the rock. The permeability of a discrete fracture is theoretically determined by its aperture. The aperture, and thereby the permeability, of the fracture vary in its plane. The permeability of a rock volume containing discrete fractures (e.g. a portion of the rock mass, a portion of a fracture zone) is determined partly by the permeability of the fractures in the volume and partly by how well they are connected with each other (connectivity). Rock without visible fractures has very low permeability. A larger rock volume contains thousands of fractures, and it is not possible to describe each fracture in detail. Instead, various macroscopic or statistical measures are used.

The most common description is to represent the permeability of a rock volume of a given size ("scale") with its hydraulic conductivity (K). In small volumes (cubes a few tens of metres or less on a side), the hydraulic conductivity will vary widely in space. On a larger scale, the spatial variation will decline (but the mean value tends to increase slightly, see /Walker et al., 1997/). In the groundwater model currently used by SKB, this spatial variation is described with a stochastic continuum model /Neuman, 1987; Norman, 1992/.

The permeability of two-dimensional geometric objects (e.g. fractures and fracture zones) can also be described by means of a transmissivity distribution. The transmissivity (T) of a fracture or a fracture zone is the total hydraulic conductivity across the entire aperture (width of zone).

Alternatively, the permeability of the rock can be described with a stochastic discrete network model (Derschowitz et al., 1999/. The model is based on a statistical description of the orientation, size, frequency and permeability of the discrete fractures. As a rule, permeability is described as a transmissivity distribution for the discrete fractures. This model concept is studied as an alternative in SR 97. Compared with a continuum model, the discrete model can provide more information on the flow on a detailed scale and on the relationship between flow and various conditions that influence radionuclide transport.

It is complicated to discuss requirements and preferences regarding the permeability of the rock, since there are different models for describing permeability and since the properties are to some extent dependent on the scale used for the description. However, experience from the extensive hydrogeological analyses carried out in SR 97 shows that it is meaningful to discuss preferences for permeability based on the concept of hydraulic conductivity on roughly a 30 m scale. The reasons are that the radionuclide transport calculations have been based on the results of hydrogeological analyses on this scale and that the comparison between the stochastic continuum model and the discrete network model show similar results. In future descriptions of the permeability of the rock, it is possible that SKB will choose other scales or other model concepts. The preferences given below can, however, be modified so that they could also be employed in these future descriptions.

7.2.2 Requirements and preferences

There are no direct requirements on transmissivity values for regional and local major fracture zones. Such fracture zones are normally associated with large flows and rapid transport pathways and are therefore not normally allowed to pass through individual deposition tunnels from a safety viewpoint (see section 4.6 and Figure 7-1). Exceptions may be made from this requirement if it is possible to show that the permeability of the fracture zone does not significantly deviate from that of the rest of the rock mass. If the fracture zones are located outside of the repository area, their permeability has a limited influence on safety. Theoretically speaking, it could even be an advantage if some of these zones had high permeability, since this could shield off the groundwater flow in the repository area.

For the rock works it is preferable that the fracture zones that have to be passed through during construction (i.e. normally local major and local minor fracture zones) have such low permeability that the seepage is moderate or that they can be sealed by normal grouting measures. Fracture zones with a low transmissivity ($T<10^{-5}$ m^2/s) do not constitute serious problems, but it is no serious obstacle if a few zones have higher transmissivity, provided they are not problematical from a construction viewpoint (e.g. high fracture density and weathering, clay). A few more complex passages can be accepted.

It is not possible to stipulate precise preferences for the permeability of individual local minor fracture zones from a safety point of view. This is because it is the geometric conditions and properties in the system of fracture zones and fractures that determine local groundwater flow and the capacity of transport pathways through the rock. However, it is generally speaking advantageous that the frequency of local minor fracture zones be low and that they have low permeability. It is preferable that the transmissivity does not exceed the values used in SR 97 /Walker et al., 1997/.

Individual deposition holes may only be intersected by individual fractures. From a safety viewpoint it is preferable that the aggregate permeability of the fractures that intersect the deposition hole be small, since this causes retardation of the radionuclide transport in the buffer/rock transition. However, the radionuclide release from the deep repository can be kept to very low values even if the groundwater flow around the deposition holes is very large. Calculations in SR 97 (/Walker and Gylling, 1998/, /Walker and Gylling, 1999/, /Gylling et al., 1999/, the Data Report /Andersson, 1999/) show that the Darcy velocity in the near field will scarcely exceed q_{max} = 0.01 m/y if the hydraulic conductivity on the 30 m scale is less than 10^{-8} m/s. In order to retain a contribution to the retardation in the buffer/rock transition, it is preferable to avoid areas where the hydraulic conductivity on a deposition hole scale exceeds 10^{-8} m/s.

The groundwater flow has a greater influence on how much radionuclide transport is retarded in the rock between the damaged canister and the biosphere. It is a clear advantage if the groundwater flow is low, even though the total release of radionuclides (and resulting doses) is not mainly determined by retardation in the rock. The Data Report's /Andersson, 1999/ compilation of the hydrogeological analyses (/Walker and Gylling, 1998/, /Walker and Gylling, 1999/, /Gylling et al., 1999/) shows that the transport resistance of the rock is considerable (F greater than 10^4 m/y, see Chapter 9) if only a limited portion of the rock mass, on the 30 m scale, has a hydraulic conductivity that exceeds 10^{-8} m/s[1)] (Figure 7-1). Other factors (such as flow-wetted surface area, transport length and hydraulic gradient) also exert an influence on the size of the transport resistance (see Chapter 9), but if permeability lies within the preferred range, the transport resistance will be considerable when the other factors have reasonable values. In other words, it turns out that the relatively weak preference regarding hydraulic conductivity with a view towards the influence on the retardation in the buffer/rock transition lies at the same level as the much stronger preference regarding the influence on the retardation in the rock.

In order for deposition to be practically possible, the flow to individual deposition holes during the deposition phase must not be too great. An upper limit has not yet been determined, but the flow should in any case be less than 10 l/min. This preference can always be satisfied by means of an active choice of deposition holes (and possible sealing measures), but it is obvious that the site will be less usable if the rock contains few suitable canister positions. To keep the inflow below 10 l/min, the local conductivity around the deposition holes (scale 10–30 m) should preferably not exceed 10^{-8}–10^{-7} m/s. This means that the construction-related and safety-related preferences regarding the permeability of the rock on a deposition hole scale are largely in agreement.

In view of the complexity of the hydraulic information and the fact that the groundwater flow is dependent on both permeability and boundary conditions, it is always necessary to set up models for groundwater flow that can calculate the function of the deep repository. This is true even if the parameter values lie within the preferable ranges.

Finally, it should be pointed out that extensive research and development efforts are still being conducted to be able to better describe groundwater flow and transport in crystalline rock. This research and development will probably show that the above preferences can largely be satisfied by an active choice of the positions of the deposition holes in the rock.

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1) The value $K<10^{-8}$ m/s can also be "derived" by means of the following simple approximations:
$F=a_rL/q$ and $q=-K\text{grad}(H)$
where a_r is the flow-wetted surface area per volume of rock, L is the transport pathway, q the Darcy velocity, K the hydraulic conductivity and grad(H) the gradient for the groundwater head. If it is assumed that grad(H) is 1%, L is 30 m (may e.g. be the distance to a major fracture zone) and a_r is approximately 1 m^2/m^3, then $F>10^4$ y/m if $K<10^{-8}$ m/s.

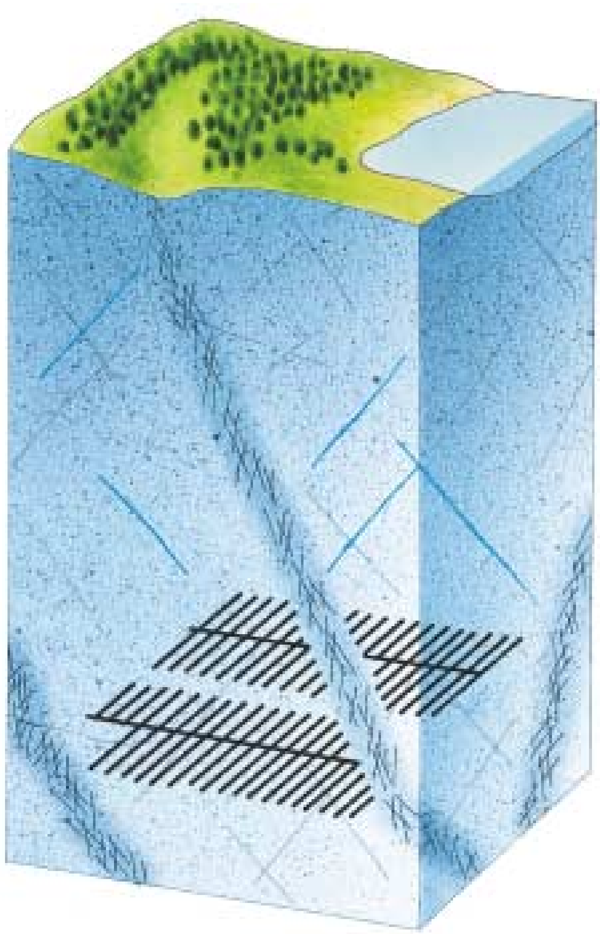

Figure 7-1. *It is an advantage if a large portion of the rock mass in the deposition area has a hydraulic conductivity (K) that is less than 10^{-8} m/s (on a scale of 30 m). Fracture zones (regional and local major ones) with large flows are normally not allowed to pass through individual deposition tunnels.*

7.2.3 Generic knowledge and knowledge obtained at different stages

Value ranges for occurrence and frequency of fracture zones are discussed under the heading “Structural geology” (see Chapter 4).

On the sites analyzed in SR 97 (data from Äspö, Finnsjön and Gideå), the hydraulic conductivity (30 m scale) of fracture zones varied between $1.5 \cdot 10^{-5}$ m/s and $2 \cdot 10^{-10}$ m/s. In a rock mass composed of discrete fractures and local minor fracture zones, hydraulic conductivity (30 m scale) varied between 10^{-6} m/s and 10^{-12} m/s. The values are based on an overall geostatistical analysis /Walker et al., 1997/.

For the municipalities investigated in the feasibility study stage, the well archive kept by SGU in compliance with Swedish law provides an approximate idea of the variation in permeability for the uppermost 100 m in different rock types within the municipality, see e.g. Folling et al. /1996/. A site investigation provides an opportunity to study the variation in permeability at greater depth and to determine (statistical) transmissivity distributions for individual fractures. The detailed characterization provides greater knowledge of the hydraulic properties of the fracture zones and fractures that intersect or come close to the investigation tunnels.

7.2.4 Suitability indicators and criteria

The permeabilities of regional and local major fracture zones are not essential suitability indicators, since these zones are avoided by adaptation of the repository layout. The geometric description of these structures is, on the other hand, very important, see section 4.4. The permeability of these zones is, however, still important to know in order to devise a good hydrogeological model of the site.

The permeability of the portion of the rock that only contains local minor fracture zones and discrete fractures should, however, be an important suitability indicator (see preferences regarding the "rock mass" above). The uncertainties in the estimate, as well as the spatial distribution, must, however, be described and handled, which complicates comparisons between sites. An overall hydrogeological modelling is necessary, even if simple approximate calculations can quickly provide a relatively good picture of the hydrogeological conditions that result from a given permeability.

During the feasibility study stage there is not enough information on the hydraulic conductivity at depth to formulate useful criteria.

A large fraction of the hydraulic conductivity values on a 30 m scale interpreted in the site investigation for the portion of the rock that is not located in interpreted fracture zones (rock mass) should be lower than 10^{-8} m/s. If this criterion is not satisfied, special requirements are made on careful adaptation of the repository to local conditions if the safety margin is to be met.

It is further advantageous if the repository is configured so that the majority of interpreted local major and local minor fracture zones that need to be passed through by access tunnels have a transmissivity lower than 10^{-5} m^2/s. If there are many zones with a higher transmissivity that are at the same time wide and clay-filled, this complicates the configuration and construction of the repository. Special attention must then also be given to possible environmental effects of groundwater drawdowns and grouting work. An assessment of the environmental impact of the construction work always needs to be done.

7.3 Porosity and storage coefficients

7.3.1 Description of parameters and their influence on functions

The flow porosity expresses the relationship between the volume of permeable cavities and fractures, and the total volume of the rock. The flow porosity influences the transport rate of non-sorbing substances, such as Cl^-, and is therefore an important parameter for transient modelling of saltwater flow. However, flow porosity is of less importance for retardation of the radionuclides that could occur in a release from a damaged canister (SR 97, Main Report, canister defect scenario /SKB, 1999a/). Most of them have good sorption capacity, whereby retardation is completely dominated by matrix diffusion and sorption, regardless of the very moderate retardation directly in the permeable fractures. The few nuclides that do not have good sorption capacity and have been able to leave canister and buffer are so long-lived that their residence time in the rock is not enough to affect the concentrations.

The storage coefficient is needed for transient evaluation of pump tests. The storage coefficient is largely dependent on the compressibility of the rock mass. It is of little importance for the function of the repository.

For individual deposition holes, there is a requirement that the porosity may not be so great that bentonite can be pressed out into large cavities and then be eroded away. However, this requirement can easily be satisfied by active choice of deposition holes and does not lead to requirements on the properties of the rock. For good near-field function (limited leakage of radionuclides from buffer to surrounding rock) it is in principle favourable that the porosity be as low as possible, but the influence is weak and there are no grounds for making requirements (see section 9.2).

7.3.2 Requirements and preferences

There are no requirements on flow porosity or storage coefficient for any of the rock's structures or surrounding rock.

Nor are there any special preferences for flow porosity. Values at repository depth should, however, not deviate greatly from normal conditions in Swedish bedrock (see next section), since experience is lacking from such (hypothetical) conditions. However, if it should turn out that a site has very abnormal porosity conditions, this does not mean that the site is unsuitable, just that further research could be needed on the importance of porosity.

7.3.3 Generic knowledge and knowledge obtained at different stages

The flow porosity of regional and local fracture zones lies in the range $10^{-3} < \varepsilon_f < 10^{-2}$, while specific storage lies in the range 10^{-6} m^{-1} $< S_s < 10^{-5}$ m^{-1}. In the rest of the rock, flow porosity lies in the range $10^{-4} < \varepsilon_f < 10^{-2}$, while specific storage is 10^{-7} m^{-1} $< S_s < 10^{-5}$ m^{-1}. The values are based mainly on estimates made within the Äspö project /Rhén (ed), 1992/, /Winberg (ed), 1996/, and /Rhén (ed) 1997/.

Flow porosity and storage coefficient can be estimated in conjunction with site investigations.

7.3.4 Suitability indicators and criteria

The parameters are not useful as suitability indicators, since they are of negligible importance for the function of the deep repository, as explained above. No criteria need to be formulated.

7.4 Properties of the groundwater

7.4.1 Description of parameters and their influence on functions

The density and viscosity of the groundwater influence hydraulic conductivity. Furthermore, density variations (which may be due to both temperature and concentration differences) give rise, via gravitation, to driving forces. The biggest temperature influence comes from the repository, but this density influence is also of relatively little importance for groundwater flow /Thunvik and Braester, 1980/. Density variations due to varying salinity can be more important and need to be taken into account in groundwater calculations /Voss and Andersson, 1993; Follin, 1995; Hartley et al., 1998/. In such calculations, however, it is necessary to take into account large-scale time-dependent changes, such as postglacial land uplift (crustal upwarping).

High salinity at depth in the bedrock may be an indication of low groundwater flux, which in principle is favourable, but in the case of transient processes caused e.g. by land uplift, the picture is not so simple – the saline water can also move. Saline groundwater also complicates the hydrogeological characterization. Furthermore, a high salinity may be unsuitable for chemical reasons, since it may disturb various barrier functions (see Chapter 8). Saline groundwater, on the other hand, reduces the risk that the area will be used in the future for abstraction of groundwater for consumption.

7.4.2 Requirements and preferences

There are no requirements or preferences regarding the density and viscosity of the water from a hydrogeological viewpoint. However, it is important to be aware of the density conditions, and they must be taken into account in groundwater modelling. From a hydrogeological viewpoint, it is not generally possible to say whether high salinities are an advantage or a disadvantage. From a chemical viewpoint, however, there is a clear requirement that the total salinity at repository level may not be too high (see section 8.4).

7.4.3 Generic knowledge and knowledge obtained at different stages

Groundwater density and viscosity are influenced by prevailing temperature and salinity. Salinity values are discussed in the chemistry sections (section 8.4). Generic knowledge of the temperature distribution (see section 6.3) is sufficient to determine the groundwater's temperature-dependent properties.

7.4.4 Suitability indicators and criteria

Groundwater density and viscosity are not primary suitability indicators from a hydrogeological viewpoint. Salinity is an important indicator from a chemical viewpoint, however. However, high and widely varying salinity conditions complicate the analysis of the suitability of a site. In any case, density variations must be taken into account in site-specific hydrogeological modelling. This parameter is therefore very important to know.

The information available during feasibility studies does not permit meaningful site-specific forecasts of groundwater flow. If the feasibility study indicates that there may be saline water at depth in the investigated area (location in relation to coast, occurrence of saline groundwater in rock-drilled wells, etc.), this probably means that the hydrogeological situation needs to be described in part as transient density-dependent flow. This should influence which data are gathered during the site investigation.

If the site investigation shows that the groundwater down to about 600–700 m has higher salinities than about 1%, it is necessary to at least partially model the groundwater flow as transient and density-dependent /Freeze and Cherry, 1979/.

7.5 Near-surface ecosystems

7.5.1 Description of parameters and their influence on functions

The near-surface ecosystems can be described in terms of identified ecosystems (forest, lake, meadow, etc.), their activity (land use, uptake rates, etc.) and transport of water and particles (meteorological/hydrological data) as well as hydrogeological description (permeability, thickness and porosity) of the soil strata. The information is needed to be able to describe turnover, transport pathways and consequences of radionuclides that escape into the environment. The near-surface conditions also influence groundwater recharge and groundwater chemistry, even though the groundwater flux at depth is very slow.

7.5.2 Requirements and preferences

There are no requirements on the near-surface conditions. The repository's isolating and retarding function should in any case be so good that adequate safety can be achieved regardless of what ground and recipient conditions prevail. Areas protected by law shall be avoided.

From a natural resource viewpoint there is a preference to avoid areas that are (or may be) important water sources, soil sources or farmland. Thick, water-bearing soil strata complicate investigations. From a natural resource viewpoint, it is preferable when building the surface facility to avoid areas where biological diversity or species worth protecting may be threatened directly or indirectly by construction of access roads and the like in virgin areas.

Data on the near-surface ecosystems are primarily valuable for building up a credible model description. In other words, good access to such data of high quality increases the credibility of the modelling.

7.5.3 Generic knowledge and knowledge obtained at different stages

Specific runoff in Sweden varies in round figures between 100 and 300 mm/y. The hydraulic conductivity of the soil strata lies in the range 10^{-9} m/s to 1 m/s. Normal soil depths lie in the range 0–30 m. Only in exceptional cases have depths up around 100 m been measured in Sweden.

The site-specific near-surface information on recipient conditions and hydrogeology can be obtained without conducting a drilling programme. Some information is obtained in conjunction with feasibility studies. But existing data may need to be compiled further. Moreover, additional and more detailed information needs to be collected during the site investigations and preparations for them.

7.5.4 Suitability indicators and criteria

Conditions in the near-surface ecosystems do not constitute geoscientific suitability indicators, but are of course taken into account in the siting of a repository. Areas with high values from a nature conservation or natural resource viewpoint are identified during the feasibility studies. If a site investigation is planned in such an area, it is a requirement that special consideration be given to these values.

A preliminary adaptation of the surface portions of the deep repository to the near-surface ecosystems is first done based on the information obtained from the feasibility study. Areas protected by law are avoided. It is a preference that areas of interest for site investigations have few competing interests and that the surface facility can be preliminarily adapted so that there is little impact on the near-surface ecosystem. A more detailed analysis and adaptation are performed at an early stage during the site investigation in connection with the choice of area for the continued site investigation, but the same basic criteria are applied.

7.6 Boundary conditions and supporting data

7.6.1 Description of parameters and their influence on functions

There are several different hydrogeological data that pertain to aspects of groundwater flow but are not included as independent model parameters in hydrogeological modelling. These include pore pressure, the groundwater's hydraulic head (the sum of pressure head and elevation head – the "groundwater table"), measured groundwater flow, characterization of recharge and discharge areas, and results of large-scale pumping and tracer tests. Such data can be used to check the reasonableness of models (supporting data) or for setting boundary conditions. Specific factors to take into account are: i) hydraulic gradient, ii) distribution of recharge and discharge areas, and iii) shoreline displacement due to land uplift etc.

The pore pressure directly influences canister function (see 7.1.1). Stipulated requirements are met by not making the repository too deep, since pore pressure is determined by depth (with very small variations).

The gradient for the groundwater's hydraulic head is the most important driving force for groundwater flow. In principle, the lower the gradient, the lower the groundwater flow. On a large scale, the gradient does not vary as much as the permeability of the rock, but is determined to a high degree by the topographical variation. Counted over large areas, the hydraulic gradient cannot be greater than the topographical gradient, but it can be lower than the topographical gradient in areas with high permeability. This means that areas with a locally small hydraulic gradient do not always have to have a low groundwater flow. If the permeability is very high, groundwater recharge will not suffice to keep the groundwater's hydraulic head at the ground surface and the gradient may be very low, even if the groundwater flow is high. Outside the Caledonian mountain range, the regional topographical gradient in Sweden is limited and generally lower than 1% (see section 4.2.3). Variations of the hydraulic gradient within such relatively flat areas are only partially linked to where the groundwater flow is great. It is primarily the permeability of the rock that determines the size of the groundwater flow.

At high salinities, where the density differences can give rise to flow forces which also drive groundwater flow, the situation is complicated by the fact that the driving force can no longer be described solely as a gradient of a hydraulic head distribution. However, this does not appreciably influence the above argument.

The distribution of recharge and discharge areas provides important information for the setting of boundary conditions for hydrogeological models, even though groundwater flux at depth is mainly determined by the permeability of the deep rock. In principle, it should be an advantage to locate the repository beneath a recharge area, since this should maximize the length of the flow paths from the repository. However, the groundwater that passes the repository will eventually come up in a discharge area, and present-day groundwater models indicate that these discharge areas are often situated not far from the repository (/Walker and Gylling, 1998/, /Walker and Gylling, 1999/, /Gylling et al., 1999/), since circulation is controlled to a high degree by structures in the rock and the local topography. The distribution of recharge and discharge areas is taken into account in the part of the safety assessment that describes effects of the near-surface ecosystems. The near-surface ecosystems are also good indicators of potential recharge and discharge areas.

Shoreline displacement alters the boundary conditions for all sites situated in near-coast areas. A future glaciation will have a far-reaching impact on groundwater flow, regardless of the location of the site. The effects of these two processes are discussed and analyzed within the framework of the climate scenario in SR 97 Main Report /SKB, 1999a/.

7.6.2 Requirements and preferences

Generally, boundary conditions and supporting data are primarily valuable in building up a credible system description. In other words, good access to such data of high quality increases the credibility of the modelling.

There are no requirements regarding hydraulic gradients, distribution of recharge and discharge areas or shoreline displacement.

There is a preference that the natural local hydraulic gradients at repository level are not higher than is normal outside the Caledonian mountain range (i.e. lower than about 1%). Very low hydraulic gradients are no further advantage, however.

It is in principle advantageous if the repository area is located beneath a local recharge area, but in view of the fact that the discharge areas are often situated not far from the repository (see above), it is doubtful whether this preference should be given particularly great weight. Adequate safety and retention capacity must in any case be demonstrated in the site-specific safety assessment.

If shoreline displacement is considerable it is necessary to take this into account in the hydrogeological modelling, since assumptions of steady states can lead to a misconception regarding groundwater flow /Voss and Andersson, 1993; Svensson, 1999/. Modelling is simplified if shoreline displacement is small, but the rate of land uplift in Sweden is so great that shoreline displacement must be taken into account everywhere along the Swedish coast north of Skåne (Scania).

There are no grounds for making requirements or preferences regarding glaciation frequency. Glaciation is analyzed as a scenario in the safety assessment.

7.6.3 Generic knowledge and knowledge obtained at different stages

Typical values in SR 97 for the natural regional gradient at repository depth are 0.05–0.2% for Äspö, 0.2–0.3% for Finnsjön and 0.5–0.6% for Gideå /Walker et al., 1997/. Regarding forecasts of shoreline displacement and future glaciations, reference is made to the climate scenario in SR 97 Main Report, Chapters 6 and 10 /SKB, 1999a/.

Information on recharge and discharge areas, as well as notions of gradients (based on topography), are probably known already from the feasibility studies. Additional, more detailed information can be gathered during the site investigations. Measurements of pore pressures and hydraulic heads can only be obtained in the site investigations.

Forecasts of shoreline displacement and glaciations are not influenced by the different phases in a site investigation.

7.6.4 Suitability indicators and criteria

Supporting data are not primarily useful as suitability indicators, but rather are needed to build up credible system descriptions. Difficult-to-interpret data, or difficulty in achieving agreement between models and supporting data, should however be negative from a siting viewpoint. Only the Caledonian mountain range is clearly unsuitable due to high gradients, but it has already been excluded for other reasons (see General Siting Study 95 /SKB, 1995b/).

Particulars on the hydraulic gradient, as well as the distribution of discharge and recharge areas, are essential for the hydrogeological understanding of the site, but vary too little to be primary suitability indicators.

Forecasts of glaciation frequency are not useful suitability indicators. Firstly, there are no special grounds for making requirements or preferences. Secondly, such forecasts must be regarded as far too uncertain to serve as a basis for site selection. The glaciation scenario is analyzed in the safety assessment, regardless of which site will be chosen.

Particulars on topographical gradient and shoreline displacement are obtained during the feasibility study. Areas with unsuitably high topographic gradients (much greater than 1%) are screened out already during the feasibility studies.

During the site investigation and the associated hydrogeological modelling, it should be possible to assess the situation for the recharge and discharge areas that are linked to the groundwater flow that passes through the repository. The information is used in the site-specific safety assessment. Good safety and isolating capacity can, however, also be obtained if the repository is located near a recharge area. It is therefore not warranted to formulate criteria in advance based on the distribution of recharge and discharge areas.

All supporting data are taken into account in the hydrogeological modelling that is carried out during the site investigation.

7.7 Summary suitability indicators – hydrogeology

The preceding sections have provided an account of which hydrogeological suitability indicators may be relevant in different stages of the siting work. The complete account of the work is found in Table A-4 in Appendix A and Table B-4 in Appendix B.

As is evident above, suitability indicators are mainly used to assess whether requirements and preferences are satisfied. Table 7-1 provides a compilation of the suitability indicators that have been preliminarily identified for hydrogeology.

Table 7-1. Suitability indicators for hydrogeology (the complete account is found in Appendices A and B).

Parameters – groupwise	Requirements or preferences	Criteria during feasibility study (FS) and during site investigation (SI)
Permeability for fracture zones and fractures	Deposition holes are not allowed to be positioned near regional or local major fracture zones. (Exceptions may be made from this requirement if it can be shown that permeability does not deviate from the rest of the rock mass.) See further fracture zones – geology. It is an advantage if a large portion of the rock mass in the deposition area has $K<10^{-8}$ m/s (on deposition hole scale). Integrated function analysis is needed. Zones that need to be passed during construction should have such low permeability that passage can take place without problems. (Zones with $T<10^{-5}$ m²/s or zones that are not difficult from a construction point of view.)	For adaptation to geometry of fracture zones and fractures – see geology. FS: No criteria. SI: A large fraction of interpreted K values in the rock mass are $K<10^{-8}$ m/s. (Otherwise need for local detailed adaptation if the safety margin is to be met.) Fracture zones that need to be passed during construction should have an interpreted transmissivity of $T< 10^{-5}$ m²/s and lack clay filling (otherwise increased attention to grouting and other construction-related risks).
Flow porosity and storage coefficient	No, since the parameters do not influence retardation of sorbing substances or long-lived non-sorbing substances (see transport).	–
Density and viscosity	Density differences influence the hydrogeological modelling, but are not grounds for requirements/ preferences (see however chemistry).	–
Near-surface ecosystems	Areas protected by law are avoided. Avoid areas for the deep repository's surface facilities where biological diversity and organisms worth protecting may be threatened and areas that are or may be important water sources, soil sources or farmland. Data on the near-surface ecosystems are primarily valuable for building up a credible model description.	FS: Areas protected by law shall be avoided. It is a preference that areas of interest for site investigations have few competing interests and that the surface facilities can be preliminarily adapted so that there is little impact on the near-surface ecosystem. SI: Criteria as above.
Supporting data (hydraulic heads, recharge and discharge areas, etc.)	Data are primarily needed to build up credible groundwater models. Advantage if local gradient <1% at repository level (but no further advantage if even lower).	FS: Areas with an unsuitably high gradient (much greater than 1%) are screened out. SI: Information on supporting data are primarily used to build up credible models.

8 Chemistry – groundwater composition

8.1 Influence on the function of the deep repository

The composition of the groundwater influences both the isolating and retarding functions of the deep repository. A review of the functions that are influenced by the composition of the groundwater reveals that the functions are influenced by a few essential hydrogeochemical parameters, see Appendix A-5. Requirements and preferences regarding these hydrogeochemical parameters are discussed in detail in the following sections in this chapter.

8.1.1 Influence on canister integrity

It is a requirement that the composition of the groundwater at the canister be such that general corrosion of the copper cannot occur (that the copper is thermodynamically stable). This means that no dissolved oxygen may be present in the groundwater around the canister for any extended period of time. It is further preferable to have a low total salinity and low concentrations of substances that influence corrosion such as sulphide, ammonium, nitrite and nitrate. Copper corrosion is discussed in the Base Scenario for SR 97 /SKB, 1999a/ based on studies by /Werme et al., 1992; Wersin et al., 1994/ as well as different reports produced by Posiva in Finland /Ahonen, 1999; Saario et al., 1999/.

8.1.2 Influence on release to the groundwater

A groundwater composition that retards fuel dissolution and leads to low solubility of released nuclides is preferable.

The model for fuel dissolution that is used in the canister defect scenario in SR 97 (Main Report /SKB, 1999a/) assumes that the surrounding groundwater is free from dissolved oxygen. To simplify the analysis, the requirement of oxygen-free conditions also ensures slow fuel dissolution. But the process of fuel dissolution is controlled in the model by oxidants that are formed by radiolysis of the water that comes into contact with the fuel.

Even if the fuel is dissolved, the constituent substances can be re-precipitated, whereby the resulting leaching-out process is controlled by the solubility of the substances. The uncertainties in the calculated solubilities are discussed with regard to input data in Bruno et al. /1997/. Solubility is above all influenced by redox conditions, pH, carbonate concentration and temperature. Preferences regarding composition are set based on the fact that the solubilities shall not be appreciably higher than what is used in the SR 97 safety assessment /SKB, 1999a/.

8.1.3 Influence on the stability of the buffer

Groundwater composition influences bentonite stability, which in turn influences the buffer's isolating and retarding capacity. It is a requirement that the buffer's swelling pressure be preserved (Main Report SR 97 /SKB, 1999a/).

If the pore water in the bentonite contains salt, which may be a consequence of either the fact that the bentonite has been saturated with saline groundwater or that salt has diffused into the pore water after saturation, swelling pressure and swelling capacity are influenced /Karnland, 1997/. Swelling pressure decreases with increasing salinity. The decrease is greatest in relative terms at a low degree of bentonite compaction.

In order for the clay gel to be chemically stable and not be dispersed to a colloidal suspension, it is further necessary that the water contain a sufficient concentration of positive ions (SR 97, Main Report, section 8.9.3 /SKB, 1999a/). The clay gel is stable if the concentration of divalent ions (calcium and magnesium) exceeds 4 mg/l /Laaksoharju et al., 1995/.

8.1.4 Influence on retardation in the geosphere

The composition of the groundwater influences several of the rock's retention properties – particularly sorption (see e.g. /Carbol and Engkvist, 1997/) and diffusion into the rock matrix. There is a risk that retention will be degraded if the water contains colloids. There is a general preference for good sorption properties in the rock, little organic complexation and negligible colloid transport. There are no absolute requirements, but overall geosphere function shall be sufficient to provide adequate safety in an integrated safety assessment. It is above all the groundwater's total salinity, pH, Eh and carbonate that influence retention properties.

8.1.5 Biosphere-related matters

Knowledge of the composition of the near-surface groundwater is needed to describe the near-surface ecosystems. This knowledge is also important to show whether more recently discovered changes are caused by the repository or are a consequence of the "natural" evolution of conditions.

8.1.6 Construction-related matters

There are a number of chemical conditions that must be taken into account in connection with the configuration and construction of the deep repository.

- Concentrations of substances that are dangerous from an occupational health viewpoint (e.g. radon) must be kept below limit values. (This can as a rule always be achieved by e.g. good ventilation.)
- The composition of the water (Cl^-, SO_4^{2-}, CO_2) can influence the choice of suitable grouting agents. But there are no grounds for requirements or preferences.
- Limited environmental impact of investigations (e.g. necessitating diversion of saline groundwater) and of construction and operation (e.g. influence of blasting gases or grouting) is a requirement.

8.2 Indications of occurrence of dissolved oxygen

8.2.1 Description of parameters and their influence on functions

There is overwhelming evidence from analyses of groundwater in crystalline rock that the groundwater does not contain dissolved oxygen at repository level. Investigations have been conducted in Sweden, Finland and Canada, see e.g. /Laaksoharju et al., 1993, and Laaksoharju et al., 1998/.

If there were dissolved oxygen in the groundwater, this could lead to corrosion of the copper canister. Sulphide in the groundwater can also attack the copper canister, see section 8.5.1. However, oxygen is much more problematical than sulphide, since oxygen can cause pitting. Indication that dissolved oxygen does not occur is therefor essential in fulfilling the fundamental safety function of an intact canister.

Occurrence of oxygen also influences fuel dissolution, solubilities and sorption properties in buffer and rock (see 8.1). For these functions as well, absence of dissolved oxygen is advantageous.

There are several different chemical parameters that can be used as indicators to see if there is any dissolved oxygen in the groundwater. Presence of dissolved oxygen in the groundwater is indicated by measurements of the redox potential (Eh). If dissolved oxygen is present, the measured values are positive. If no dissolved oxygen is present, which is the case in deep groundwaters, the redox potential is determined by the iron II/III ratio, or by sulphide and other sulphur compounds in the water. Then the values are normally negative. The Eh is measured continuously during hydrogeochemical borehole investigations and provides a good idea of conditions already during the actual investigation campaign. In some cases it can be difficult to obtain reliable Eh values, such as under difficult sampling conditions and/or if the concentrations of iron and sulphide are low. Then the occurrence of Fe^{2+}, Mn^{2+} or HS^- is in itself proof of the absence of dissolved oxygen. These substances are analyzed on samples taken during the investigation campaign.

8.2.2 Requirements and preferences

It is a requirement for canister isolation that, under undisturbed conditions and shortly after the repository has been closed, no dissolved oxygen should occur at repository depth (see 8.1.1 and Figure 8-1). In order for this requirement to be satisfied, at least one of the indicators negative Eh, occurrence of Fe^{2+} or occurrence of HS^- must be satisfied, or it must otherwise be possible to prove that dissolved oxygen does not occur.

8.2.3 Generic knowledge and knowledge obtained at different stages

Measurement data from deep groundwaters in Sweden and Finland /Laaksoharju et al., 1993, and Laaksoharju et al., 1998/ show that the above requirement is always met. At repository depth, Eh values are negative, concentrations of F^{2+} lie in the range 5 µg/l–10 mg/l, and sulphide concentrations lie in the range 0.01–5 mg/l.

General siting studies or feasibility studies do not contribute any new knowledge about the aforementioned oxygen indicators compared with the general knowledge that already exists. The essential site-specific information on the parameters is obtained in water samples from the deep boreholes that are drilled in conjunction with site investigations. Detailed characterization (investigations from tunnels) may contribute new knowledge in the portion of the rock that has very low permeability.

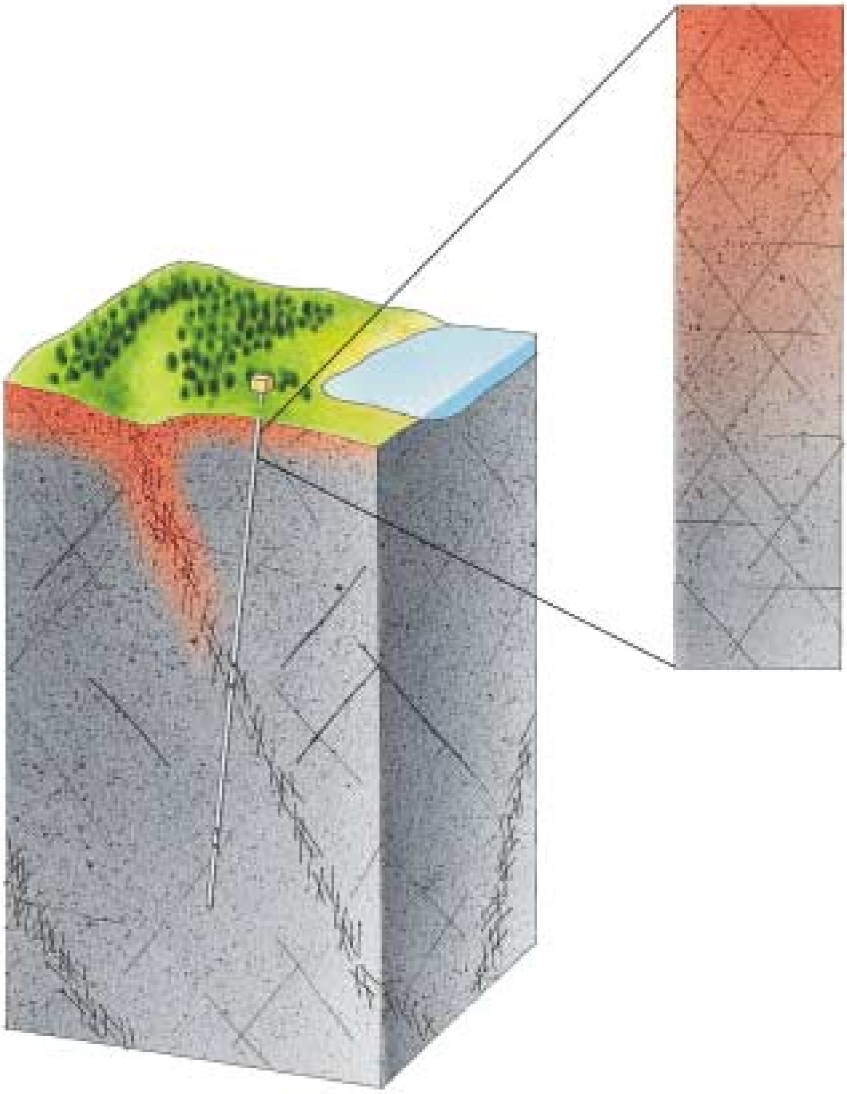

Figure 8-1. *Dissolved oxygen must not occur at repository depth. Oxygen dissolved in the surface water is normally consumed in the soil zone, but may reach greater depth in fracture zones.*

8.2.4 Suitability indicators and criteria

It is obvious that parameters that can indicate the presence of dissolved oxygen are very important suitability indicators, since they are linked to requirements. Furthermore, the parameters can be successfully determined in a site investigation.

No meaningful criteria can be set up before the site investigations are completed. However, experience shows that the above requirement can be expected to be satisfied.

During site investigation, at least one of the indicators negative EH values, occurrence of Fe^{2+} or occurrence of HS^- must be satisfied. If none of the indicators can clearly demonstrate the absence of dissolved oxygen, a deeper chemical assessment is required. Studies of Fe(II) and sulphide minerals, such as pyrite and biotite, can be used to further clarify the redox conditions. If not even these further studies are able to demonstrate oxygen-free conditions, the site must be abandoned.

8.3 pH

8.3.1 Description of parameter and its influence on functions

Extensive experience and data are available on pH conditions in crystalline rock. pH is controlled for the most part by the calcite/carbonate system. The pH of the groundwater primarily influences canister corrosion, sorption (/Carbol and Engkvist, 1997/, /Yu and Neretnieks, 1997/) and solubilities of radionuclides /Bruno et al., 1997/ (see also SR 97 SR 97 Main Report Chapter 8 /SKB, 1999a/).

8.3.2 Requirements and preferences

It is a preference that the pH of the groundwater below 100 m lie between 6 and 10. All pH values within this range are in principle equally suitable. There are no preferences for the groundwater above a depth of 100 m. The preference is based above all on the fact that the knowledge base for sorption parameters ("K_d values") used in the safety assessment derives from measurements within the preferred pH range. If values lie outside the range, the database needs to be augmented.

8.3.3 Generic knowledge and knowledge obtained at different stages

Measurement data from deep groundwaters in Sweden and Finland show that the pH below a depth of 100 m is between 6 and 10 as a rule, but deviations (higher values) occur, for example at Stripa /Laaksoharju et al., 1993 and Laaksoharju et al., 1998/. Lower pH values occur above 100 m.

Different general siting studies or feasibility studies do not contribute any new knowledge about pH compared with the general knowledge that already exists. The essential site-specific information on the parameters is obtained in water samples from the deep boreholes that are drilled in conjunction with site investigations. Detailed characterization (investigations from tunnels) may contribute new knowledge about pH in the low-permeable rock.

8.3.4 Suitability indicators and criteria

pH is a useful suitability indicator since it is linked to preferences. The parameter can also be successfully determined in a site investigation.

No meaningful criteria can be set up during feasibility studies. However, experience shows that the above preferences can be expected to be satisfied.

In the site investigations, quality-approved measured pH values should lie within the stipulated preference interval ($6<pH<10$) below the 100 m level. If this criterion is not satisfied, a deeper analysis, augmentation of the database for sorption parameters and possibly extended sampling are needed. If the analysis shows that the pH deviates significantly from stipulated ranges, the suitability of the site may be questioned.

8.4 Total Dissolved Solids (TDS)

8.4.1 Description of parameters and their influence on functions

Total salinity (TDS = "Total Dissolved Solids") mainly influences the bentonite's stability and sorption of radionuclides. If TDS is very high, the bentonite's swelling capacity decreases (Karnland /1997/), and at concentrations higher than 100 g/l the buffer's swelling capacity may have declined by more than half for a bentonite with a density of 2,000 kg/m^3. High salinities also reduce the sorption capacity in the rock of many radionuclides (Carbol and Engkvist /1997/). Very high salinities (TDS>200 g/l) in combination with very low pH (pH<3) also influence the stability of copper (SR 97 Main Report section 8.9 /SKB, 1999a/). However, such low pHs cannot occur at repository depth due to the reaction between minerals and water /Stumm and Morgan, 1996/.

8.4.2 Requirements and preferences

It is a requirement that TDS <100 g/l in the deposition area (Figure 8-2). Thorough investigations are required to clarify whether the bentonite can withstand higher concentrations with undiminished swelling capacity.

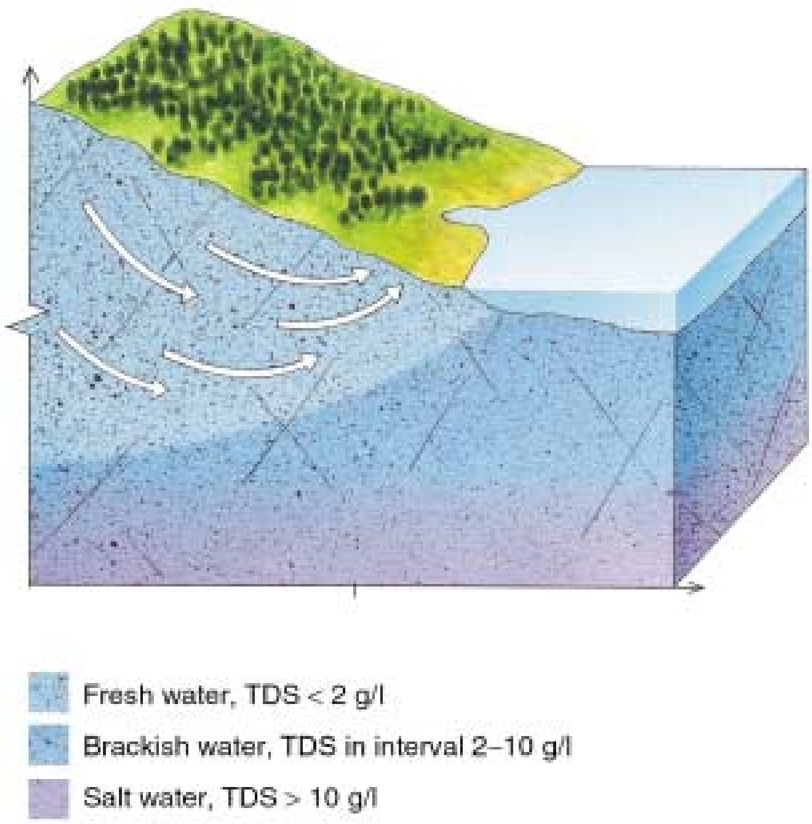

Figure 8-2. *Total salinity must be less than 100 g/l in the deposition area.*

8.4.3 Generic knowledge and knowledge obtained at different stages

Measurement data from deep groundwaters in Sweden show that down to a depth of 1,000 m, TDS lies within the interval 0–35 g/l. Even higher concentrations occur at greater depths. Concentrations of up to 100 g/l have been measured at a depth of 1,700 m /Laaksoharju et al., 1993, and Laaksoharju et al., 1998/. The depth to groundwater with high salinities is as a rule greater inland than on the coast. In Finland, a TDS of 70 g/l has been measured at depths below 800 m /Pitkänen et al., 1998/.

Different general siting studies or feasibility studies do not contribute any new knowledge on TDS or content of essential ions compared with the general knowledge that already exists. The essential site-specific information on the parameters is obtained in samples/measurements from the deep boreholes that are drilled in conjunction with site investigations. Detailed characterization may contribute new knowledge on TDS in the portion of the rock that has very low permeability.

8.4.4 Suitability indicators and criteria

TDS at repository level is a useful suitability indicator.

No meaningful criteria can be set up before the site investigations are completed. However, experience shows that elevated TDS can be expected in locations relatively near the coast and in relatively flat terrain.

In the site investigations, all quality-approved TDS values measured at planned repository depth shall meet the above requirement. Occasional higher values can be accepted if it can be shown that the water is located in areas that can be avoided and that the water will not flow to the repository area.

8.5 Organic substances and other components in the groundwater

8.5.1 Description of parameters and their influence on functions

DOC stands for “Dissolved Organic Carbon” and designates the quantity of dissolved organic carbon measured in the groundwater. DOC is thereby a measure of the quantity of organic matter measured as total organic carbon in solution. The amount of organic matter in the water influences e.g. the bacterial transformation of sulphate to sulphide (SR 97 Process Report section 4.7.10 /SKB, 1999b/, /Pedersen and Karlsson, 1995/).

The sulphide concentrations in Swedish groundwaters are generally limited by the fact that sulphide precipitates as solid minerals when the sulphide concentrations become sufficiently high. The solid minerals are formed above all by reaction with iron. Furthermore, the buffer limits the transport of sulphide up to the canister. Calculations show that it would take longer than 10 million years to corrode a copper canister 1 cm, even if the concentration of sulphide were around 1 mg/l /SKB, 1999b/.

High concentrations of nitrogen and phosphorus compounds are undesirable since they stimulate bacterial growth. High concentrations of nitrogen compounds can cause stress corrosion cracking in copper /Benjamin et al., 1988; SR 97 Process Report 3.7.6, SKB, 1999b; Saario et al., 1999/.

It is necessary to know the quantities and types of nutrients that remain in the rock when the repository is closed. If these quantities are acceptable at closure, there are no processes in the rock which can in the long run lead to an increase to an unacceptable level.

The stability of the bentonite is influenced by the concentrations of Na^+, Ca^+ and Mg^+. Low concentrations can reduce the stability of the bentonite gel, from which colloidal particles can then be carried away by the groundwater /Laaksoharju et al., 1995/.

The occurrence of colloids, humic and fulvic acids, free gas (as H_2, N_2, CH_4, CO_2, He and Ar) and bacteria influence conditions for radionuclide transport. For example, sorbing radionuclides can be transported with the water if they adhere to colloidal particles in the groundwater. However, the transport process is completely negligible at the colloid concentrations that normally occur in deep groundwaters /SKB, 1999a; Allard et al., 1991/. In a similar manner, gas bubbles and bacteria can be "carriers" of radionuclides. Complexation with humic and fulvic acids can reduce the sorption of some of the radionuclides.

The concentrations of Ra and Rn influence what occupational safety measures are needed during repository construction. These concentrations are linked to the concentration of U and Th in the bedrock and can thus be estimated based on knowledge of the rock type (see 4.4).

A large number of other components in the water are also measured during analysis of groundwater composition. This is needed for a proper chemical understanding, but no other components are directly linked to requirements or preferences.

8.5.2 Requirements and preferences

There are no grounds for requirements regarding organic substances or other components in the groundwater.

Near-surface waters (0–100 m) should contain more than 10 mg/l DOC to ensure reduction of dissolved oxygen in infiltrating groundwater /Banwart (ed) 1995/. Lower concentrations are desirable at repository depth, the lower the better.

Low values of ammonium (NH_4^+) are preferable, but how low values are desirable is still the subject of investigation.

It is an advantage if the concentrations of $[Ca^{2+}]+[Mg^{2+}] > 4$ mg/l at repository depth (SR 97 Main Report, section 8.9.3 /SKB, 1999a/, /Laaksoharju et al., 1995/). Higher values are no further advantage, however.

Low concentrations of colloids (<0.5 mg/l) and absence of free gas (bubbles) at repository level are preferable, since these parameters can influence the transport of radionuclides in the geosphere. The occurrence of dissolved H_2 or CH_4, on the other hand, indicates reducing conditions and is advantageous from the viewpoint of the deep repository.

Low concentrations of Ra and Rn are preferable for the working environment, but suitable protective measures (ventilation) can always be adopted if the levels are too high.

8.5.3 Generic knowledge and knowledge obtained at different stages

Measurement data from deep groundwaters in Sweden and Finland show that at the planned repository depth, DOC is as a rule less than 10 mg/l. Considerably higher concentrations can occur during and just after the construction phase, but they will quickly come down to lower levels as the organic matter reacts with the entrapped oxygen /Puigdomenech et al., 1999/.

The highest sulphide concentrations that have been measured in Swedish groundwaters lie around 1 mg/l. Sulphide concentrations of 5–10 mg/l have been measured in rock volumes beneath sea sediment, where extensive sulphate reduction occurs.

Measurement data from deep groundwaters in Sweden and Finland show that at the planned repository depth, the concentrations of [Ca^{2+}] and [Mg^{2+}] lie within the preferred ranges. [Ca] lies in the interval 21–1,890 mg/l and [Mg] in the interval 1–110 mg/l /Laaksoharju et al., 1993, and Laaksoharju et al., 1998/.

The median concentration of colloids in the groundwater at the planned repository depth is less than 0.05 mg/l /Laaksoharju et al., 1995/. Considerably higher concentrations can occur during the construction phase.

Different general siting studies or feasibility studies do not contribute any new knowledge on DOC or other chemical parameters at repository depth. The essential site-specific information on the parameters is obtained in water samples from the deep boreholes that are drilled in conjunction with site investigations. Detailed characterization contributes new knowledge about conditions in the low-permeable rock at repository level, but there is a risk of temporary disturbances during the construction period due to mixing processes.

8.5.4 Suitability indicators and criteria

None of the above preferences are sufficiently important to constitute grounds for suitability indicators. The concentrations are essential to know, since they comprise important information concerning chemical and hydrogeological evolution of the site. Good knowledge of these conditions leads to better understanding, thereby reducing the non-quantifiable uncertainty regarding the properties and future evolution of the site.

It is not possible to formulate criteria for the other parameters solely on the basis of the knowledge that exists during a feasibility study. Special attention and investigations may, however, be necessary if concentrations measured during a site investigation deviate from the preferred.

8.6 Summary suitability indicators – chemistry

Table 8-1 provides a compilation of the suitability indicators that have been preliminarily identified for hydrogeochemical composition. The complete account of the work is found in Tables A-5 in Appendix A and B-5 in Appendix B.

Table 8-1. Suitability indicators for hydrogeochemical composition. (The complete account is found in Appendices A and B).

Parameters – groupwise	Requirements or preferences	Criteria during feasibility study (FS) and during site investigation (SI)
Dissolved oxygen	Requirement: Absence of dissolved oxygen at repository level (indicated by negative Eh, occurrence of Fe(II) or occurrence of sulphide).	FS: No criteria (no data available) but there is no reason to believe that the requirement cannot be met. SI: At least one of the indicators Eh, Fe^{2+}, HS^{-} must be satisfied.
pH	Preference: Undisturbed groundwater at repository level should have a pH in the range 6–10.	FS: No criteria (no coupling to surface water). SI: below the –100 m level, quality-approved values should lie in the range 6–10.
Total dissolved solids (TDS)	Requirement: TDS<100 g/l	FS: No criteria SI: Quality-approved measured TDS at repository level must meet this requirement. Occasional higher values can be accepted if it can be shown that the water is located in areas that can be avoided.
Other chemical parameters	Preference: [DOC]<20 mg/l, colloid concentrations <0.5 mg/l, low ammonium concentrations $[Ca^{2+}]+[Mg^{2+}]>4$ mg/l at repository depth, low concentrations of Rn, Ra.	FS: – SI: Attention to whether measured concentrations deviate from preferences.

9 Transport properties of the rock

9.1 Influence on the function of the deep repository

The retarding function of the deep repository is dependent to a large extent on the transport properties of the rock, but the transport properties also have some influence on the isolating function of the deep repository. Appendix A-6 summarizes how the transport properties of the rock influence these functions. The transport processes in the rock, primarily radionuclide transport, are thoroughly analyzed in SR 97 (Main Report, Chapter 9 /SKB, 1999a/).

9.1.1 Influence on integrity of canister and buffer

To guarantee a suitable chemical environment for the canister and buffer, groundwater of unsuitable composition should not be able to flow to the repository area for any extended period of time. The stable chemical environment in the rock (see Chapter 8) shows that no specific requirements need to be made on the rock in this respect, however.

9.1.2 Influence on the retarding capacity of the geosphere

The importance of some retardation is dependent to a high degree on how great the retardation is in relation to the half-lives of the various radionuclides. In general, retardation can reduce the release of relatively short-lived nuclides by giving them time to decay, while relatively long-lived nuclides may remain more or less unaffected. The magnitude of the retardation can vary greatly between different nuclides (different sorption properties) and between different conditions in the rock. The size of the groundwater flow is often of crucial importance.

The transition between buffer and rock can entail a considerable retardation of released radionuclides. The retardation in the transition is dependent on the groundwater composition (or the Darcy velocity) on a deposition hole scale and the geometry of the fractures that intersect the deposition hole /Moreno and Gylling, 1998/. Calculations in SR 97 (Main Report, section 9.11 /SKB, 1999a/) show that the buffer/rock transition is of importance in retarding several nuclides, and conditions leading to high retardation are naturally preferable. There are, on the other hand, no grounds for requirements, since the calculations also show that the release to the biosphere can be kept below levels set in SSI's regulations /SSI, 1998/, even if the retardation in the transition is neglected.

The retardation in the rock itself (the geosphere) is determined mainly by the "transport resistance" ("F parameter") in the geosphere, which is dependent on groundwater flow, flow paths and the flow-wetted surface area (see e.g. /Andersson et al., 1998b/), by the diffusivity and porosity of the rock matrix and by the capacity of the radionuclides to sorb on the rock matrix. The sorption capacity of different substances is determined to a large extent by their "speciation", which is in turn dependent on the composition of the groundwater. Consequence calculations in SR 97 (SKB, 1999, Main Report, section 9.11 /SKB, 1999a/) demonstrate that the "transport resistance" has a very great influence on retardation. The transport resistance also influences the breakthrough time for nuclides with little sorption, but very long-lasting releases of nuclides with a long half-life and negligible sorption are not affected at all by retardation in the rock. Large transport resistances in the geosphere are of course preferable, but it is not possible to stipulate a more precise requirement than that the aggregate barrier function shall suffice to ensure adequate safety. The release to the biosphere can be kept below levels set in SSI's regulations /SSI, 1998/, even if not all transport pathways from repository to biosphere have a large transport resistance.

9.2 Flow parameters on deposition hole scale

9.2.1 Description of parameters and their influence on functions

In a repository of the KBS-3 type, groundwater flow and fracture aperture influence the retardation of radionuclides between buffer and rock /Moreno and Gylling, 1998/. The influence is relatively limited, however, and calculations carried out within the framework of SR 97 (Main Report, section 9.11 /SKB, 1999a/) show that at higher values of the groundwater's Darcy velocity than approximately 0.01 m/y, retardation is no longer dependent on groundwater flow. The importance of the retardation in the buffer/rock transition is further dependent on which nuclides are being considered (see 9.1.2) and whether there are other obstacles to transport in the near field. If the release is limited by a small hole in the canister, the buffer/rock transition is of little importance. Due to these different conditions, it is really not possible to stipulate any special preferable maximum value of groundwater flow on a deposition hole scale (even if it is possible to specify an approximate upper limit where the groundwater flow influences the release from the near field).

Extremely large groundwater flows or fracture apertures could damage the buffer by creating conditions for its mechanical erosion (SR 97 Process Report /SKB, 1999b/. However, such high flows can, if they occur at all, always be avoided by a suitable choice of deposition holes.

9.2.2 Requirements and preferences

From a transport viewpoint, there is no reason to make requirements on groundwater flux or apertures on a deposition hole scale. As long as the buffer is in place, this – together with the solubility limits – provides a considerable retardation of the release from a damaged canister. It is, however, a requirement that the flow and the apertures not be so large that the buffer is damaged. Apertures of centimetre size are needed for the buffer to be damaged. The requirement of avoiding fractures with such apertures can always be met by a suitable choice of deposition holes.

From a transport viewpoint there is a preference for low water flux and small apertures. It is therefore not possible to specify an upper limit for preferable Darcy velocity (or hydraulic conductivity), but it is preferable that canister positions can be found in a large portion of the rock which, on a canister hole scale, have a lower Darcy velocity than 0.01 m/y, since lower fluxes entail increased retardation. In any case, however, a final assessment of whether the near-field properties are good enough needs to be made within the framework of an integrated safety assessment.

9.2.3 Generic knowledge and knowledge obtained at different stages

The Darcy velocity on a deposition hole scale is a calculated parameter. It exhibits considerable spatial variation. In SKB 91 /SKB, 1992/, the Darcy velocity in Finnsjön was calculated to lie in the range 10^{-5}–0.1 m/y. For the various sites (Äspö, Finnsjön, Gideå) that have been analyzed within the framework of SR 97, the calculated Darcy velocities lie within the same range (/Walker and Gylling, 1998/, /Walker and Gylling, 1999/, /Gylling et al., 1999/). The spatial variation within each site is considerable, but the values are typically 100 times lower for Gideå compared with the other sites.

Different regional studies or feasibility studies do not contribute any new knowledge about groundwater flux or fracture apertures at repository depth compared with the general knowledge that already exists.

In a site investigation, groundwater flow can be calculated by modelling based on the permeability that can be estimated from hydraulic tests in boreholes. The modelling results provide statistical information that can be used to judge the spatial variation of the Darcy velocity on a deposition hole scale. There are also methods for direct measurement of groundwater flux in a part of a borehole /e.g. Rouhianen, 1993/. The methods are useful but they also only provide information in a number of points that can be used as a statistical sampling. It is only during detailed characterization or later that individual canister positions can be evaluated.

9.2.4 Suitability indicators and criteria

Groundwater flux (Darcy velocity) on a deposition hole scale should be a useful suitability indicator during a site investigation. But the preference is not of very great importance. In formulating criteria, it is also necessary to take into account the uncertainties in the estimate of the spatial variation of the groundwater flow.

Excluding deposition holes with such great groundwater flux and such large apertures that buffer function can be adversely affected may be necessary in selecting individual canister positions, but does not influence overall siting since these conditions can only apply to very local areas in the rock. Such active choices can, however, not be made until during detailed characterization or a deposition stage.

Fracture apertures on a deposition hole scale are only of limited importance as suitability indicators, since they are as a rule of limited importance for function.

No information on the groundwater flow on a deposition hole scale is available during feasibility studies.

During the site investigation, it is judged to be an obvious advantage if the estimated Darcy velocity on a deposition hole scale is lower than 0.01 m/y for a large number (in a statistical sense) of positions in the rock. Neither safety nor retardation in the rock need be threatened if the criterion is not met, however. In any case, a final assessment of the near-field properties needs to be made within the framework of an integrated safety assessment.

9.3 Properties of flow paths

9.3.1 Description of parameters and their influence on functions

The models for transport in rock may undergo development over the coming years, which means that the parameters used here may change. The fundamental arguments presented here will probably not have to be changed, however, even though it may turn out that the methods used today to describe transport underestimate retardation and thereby exaggerate the preferences that should be made on the rock from a transport viewpoint.

The transport of radionuclides through the rock takes place chiefly by advection in the open fractures. If the substances dissolved in the water do not interact with their surroundings, the transit time is determined by the water's "travel time" (t_w), which can be expressed as the length of the transport pathway (L) divided by the quotient of the Darcy velocity (q) and the flow porosity (ε_f). If the substances can furthermore diffuse into the rock matrix and sorb there, this will give rise to a considerable retardation, and the resultant "transport velocity" is then determined essentially by the Darcy velocity and the geometry of the fractures, and by the diffusion and sorption properties of the matrix. The flow porosity is of subordinate importance in this case.

If a simplified flow geometry is assumed, e.g. flow through rectangular channels, the controlling groups of parameters for matrix diffusion can be expressed as the product of the "transport resistance" or "F parameter" and a group of parameters containing the sorption coefficient (K_d value), the diffusion coefficient and the matrix porosity. The F parameter can be expressed in different ways, for example:

$F=a_rL/q =(a_w/\varepsilon_f)L/q=a_wt_w$

where a_r is the flow-wetted surface area per volume of rock and a_w is the flow-wetted surface area per volume of flowing water (see e.g. /Andersson et al., 1998b/). The latter formulation is used in the model FARF31, which is used in SR 97. The greater the transport resistance, the greater the retardation. It should be noted that a_w and t_w are strongly and inversely correlated via their linear dependence on the flow porosity, but that the product F is not directly dependent on the flow porosity.

In addition to advective transport, mixing and velocity differences occur in the groundwater. This residual term is usually called hydrodynamic dispersion. In the groundwater calculations that are performed as a basis for the safety assessment, however, the advective flow field is described in relatively great detail. Different deposition holes will be connected with different transport pathways. The different transport pathways can have drastically different groundwater flows. The explicit modelling of these velocity variations enables the somewhat problematical concept of dispersion to be minimized to small-scale velocity variations. Dispersion will thereby be of subordinate importance for radionuclide transport. Dispersion is represented by a Peclet number, where large Peclet numbers mean that dispersion is small compared with advection.

The importance of some retardation is nuclide-specific. Sorption coefficients (K_d values) and matrix diffusivity are nuclide-specific (see section 9.4). Furthermore, if retardation is great in relation to the nuclide's half-life, the nuclide will decay before it has passed through the geosphere, whereas if retardation is small in relation to half-life it will have a negligible influence. Due to these relationships it is really not possible to specify any particularly preferable minimum value of the transport resistance (F parameter).

From the calculations in SR 97, where several different values of the F parameter were studied in different calculation cases (Main Report, section 9.11 /SKB, 1999a/), the general conclusion can nonetheless be drawn that the geosphere has a considerable capacity for retarding important radionuclides if $F>10^4$ y/m. The importance of retardation in the geosphere decreases rapidly for lower values. This semi-qualitative assessment also agrees with conclusions that can be drawn from SKI's safety assessment SITE-94 /SKI, 1996/ or the different Finnish safety assessments (e.g. TILA-99 /Vieno and Nordman, 1999/).

9.3.2 Requirements and preferences

There are no grounds for requirements on the F parameter or other flow-related transport parameters. The release to the biosphere can be kept below levels set in SSI's regulations even if not all transport pathways from repository to biosphere have a large transport resistance.

It is a preference that there be a considerable retardation of important radionuclides in the geosphere (Figure 9-1). A quantitative preference can be expressed in the form of the transport resistance (F parameter), where the Darcy velocity, flow distribution and flow-wetted surface area per volume of rock (or similar parameters) are such that a large fraction of all the flow paths have $F>10^4$ y/m. (At reasonable values of a_r (1.0 m^{-1}) and L (100 m), this leads to the preference $q<0.01$ m/y, but account must be taken of the fact that q and a_r vary and may be correlated, see also section 7.2.2.) In any case, a final assessment needs to be made within the framework of an integrated safety assessment.

There is no reason to make special preferences regarding flow porosity or hydrodynamic dispersion.

9.3.3 Generic knowledge and knowledge obtained at different stages

The calculated values of the F parameter /Andersson, 1999/ used in SR 97 are based on the results of the groundwater flow calculations (/Walker and Gylling, 1998/, /Walker and Gylling, 1999/, /Gylling et al., 1999/) combined with estimation of the flow-wetted surface area per volume of rock /Andersson et al., 1998b/. The values are shown in Table 9-1. It is clear that all sites contain a large number of canister positions connected with transport pathways with the F parameter within the desired value range. At Äspö and Finnsjön there are also several pathways that lie outside the value-preferred range. Nevertheless, SR 97 concludes that safe final repositories can be build on these sites. Furthermore, retardation could be considerably improved if it were possible to deposit canisters only in positions connected with transport pathways with high transport resistance. This option for a greatly improved repository layout has not been taken into account in SR 97 /SKB, 1999a/.

Regarding values for other parameters, reference is made to the Data Report for SR 97 /Andersson, 1999/.

Feasibility studies contribute knowledge on topography and an estimate of the large-scale groundwater recharge, which provides some information on groundwater flow and transport pathways. Since data on hydraulic parameters are otherwise lacking at this stage, it is not possible to obtain a detailed picture of groundwater conditions in a feasibility study.

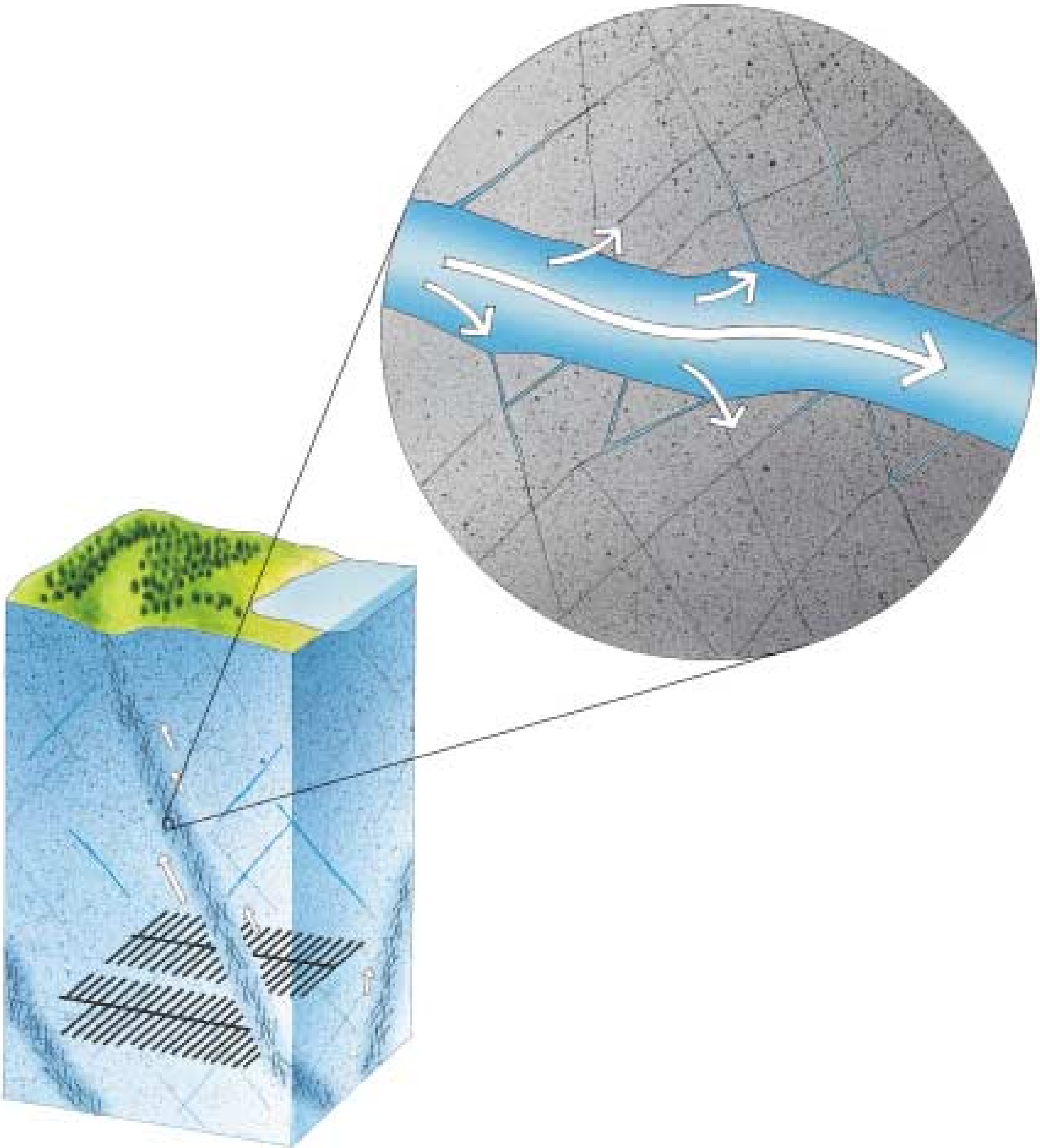

Figure 9-1. High transport resistance is preferable (low groundwater flow and high accessibility to the rock matrix).

Table 9-1. Calculated values of F (y/m) for different flow paths in SR 97 (from Andersson, 1999).

Proportion of flow paths with higher F factor	Äspö F >	Finnsjön F >	Gideå F >
50%	10^5	$6 \cdot 10^5$	$2 \cdot 10^6$
95%	$8 \cdot 10^2$	$3 \cdot 10^3$	$4 \cdot 10^5$

Essential knowledge of the rock's hydrology is obtained in site investigations. But it is unclear whether it will be possible to estimate the transport resistance (F) for different transport pathways with high precision. It can probably not be measured directly, but must be estimated by modelling /Andersson et al., 1998b/. The result is a statistical distribution that describes the spatial variation and the uncertainties.

Detailed characterization can make it possible to select canister positions that are connected with transport pathways with high transport resistance.

9.3.4 Suitability indicators and criteria

The transport resistance F is a useful suitability indicator during the site investigation, since retardation in the rock is an important (although not a crucial) barrier. Uncertainty in the estimation of the spatial distribution must be taken into account, however. It should be noted that the transport resistance is only subject to a preference, not a requirement.

Neither flow porosity nor dispersion are useful suitability indicators, since they are not of essential importance for retention.

No meaningful criteria can be formulated based on the information that can be obtained from a feasibility study or general siting study.

During the site investigation it should be possible to show that a large fraction of the estimated statistical distribution of the flow paths have a transport resistance $F>10^4$ y/m. If this criterion is not satisfied, the safety margin can probably be increased if it is possible to demonstrate convincingly that the unsuitable flow paths can be avoided later (during repository construction) by the choice of a suitable repository layout and suitable canister positions. In any case, a final assessment needs to be made within the framework of an integrated safety assessment.

9.4 Properties of the rock matrix along flow paths

9.4.1 Description of parameters and their influence on functions

Sorption can occur on the surfaces of microfractures inside the rock matrix, i.e. combined with matrix diffusion, and on larger fracture surfaces in direct contact with the flowing water. These mechanisms are a prerequisite in order for the rock to provide meaningful retardation of radionuclides released from defective canisters. SKB's migration models (FARF31) mainly deal with sorption in the matrix, while sorption directly on the macrofractures is neglected. Information on sorption, as well as the diffusivity and porosity of the rock matrix, is needed to be able to determine the importance of sorption in the rock matrix.

The sorption of radionuclides dissolved in the groundwater is described in the safety assessment's migration models with the sorption coefficient K_d, which indicates the distribution of radionuclides between the water and the rock. The K_d values are nuclide- (or rather element-) specific and are furthermore dependent on the groundwater chemistry. In principle, they are also dependent on the composition of the rock, but experience shows that this dependence can largely be neglected /Carbon and Engkvist, 1997/. The K_d values are thereby only indirectly site-specific, via the composition of the groundwater, and are therefore not dealt with any further here, since preferences regarding groundwater composition from this aspect have already been discussed in Chapter 8.

Matrix diffusion is also determined by the properties of the rock matrix (diffusivity and porosity). These properties can moreover be assumed to decline at a given distance from the fracture, which is why models as a rule also contain a stipulated maximum "penetration depth", which is conservative estimate of how much of the rock matrix is accessible for diffusion. For symmetry reasons, the penetration depth cannot be greater than the distance between different fractures, but for sorbing nuclides the actual penetration depth is much shorter. For sorbing nuclides, a limited accessible penetration depth has a negligible influence, provided it is at least several centimetres (see e.g. SKI Project 90 /SKI, 1991/), while accessibility to greater depths can be important for short-lived non-sorbing nuclides.

The density of the rock matrix does not influence sorption. Although density does occur in the formula for the transport calculations, this is because sorption data are reported per kg. Furthermore, the natural range of variation is small.

9.4.2 Requirements and preferences

There are not direct requirements on the rock's diffusivity D_e or matrix porosity ε_r.

There is a preference that most conceivable transport pathways for groundwater from the repository should make a substantial contribution to retardation. It is thereby desirable that matrix diffusivity and matrix porosity not be much lower (by a factor of 100 or more) than the value ranges analyzed in SR 97 (see / Ohlsson and Neretnieks, 1997/). The maximum accessible penetration depth should at least exceed a couple of centimetres. Minor deviations from these values are of little importance, but if diffusivity and porosity are zero, no retention occurs.

9.4.3 Generic knowledge and knowledge obtained at different stages

Value ranges for K_d and matrix diffusivity are nuclide-specific and dependent on groundwater chemistry (see /Carbol and Engkvist, 1997/ for K_d and /Ohlsson and Neretnieks, 1997/ for diffusivities and porosities).

Feasibility studies make no further contribution to the general knowledge on diffusivity and porosity. In site investigations, matrix diffusivity and matrix porosity can be determined by laboratory tests on drill cores and possibly also in-situ from boreholes.

9.4.4 Suitability indicators and criteria

Matrix diffusivity and matrix porosity are not expected to vary substantially between different sites. The parameters are therefore only meaningful as suitability indicators in the unlikely event that matrix diffusivity and matrix porosity should be found to be very low (see above). The parameters are important to know since they are included in retention calculations.

No meaningful criteria can be formulated based on information that is available during feasibility studies.

Measured values of matrix porosity/diffusivity should not be appreciably lower than the values normally encountered in Swedish crystalline bedrock /Ohlson and Neretnieks, 1997/. If the measured values are more than 100 times lower than these normal values, special attention is required in the coming safety assessment.

9.5 Summary suitability indicators – transport properties of the rock

The preceding sections have provided an account of which suitability indicators for transport properties may be relevant at different stages of the siting work. The complete account of the work is found in Tables A-6 in Appendix A and B-6 in Appendix B. Table 9-2 provides a compilation of the suitability indicators that have been preliminarily identified for the transport properties of the rock.

Table 9-2. Suitability indicators for the transport properties of the rock. (The complete account is found in Appendices A and B).

Parameters – groupwise	Requirements or preferences	Criteria during feasibility study (FS) and during site investigation (SI)
Flow parameters on deposition hole scale	Preference for low (and even) flows on deposition hole scale. Large fraction with groundwater flow (Darcy velocity) $q<0.01\,m/y$[2]. Evaluated within the framework of an integrated safety assessment.	FS: – SI: Advantage if the estimated Darcy velocity (on a scale of 10 m^2) is lower than 0.01 m/y for a large number of positions in the rock. Final judgement is made within the framework of a safety assessment.
Flow-related transport parameters (q, a_r, $a_r L/q$, etc.)	Preference for high F. Large fraction of flow paths with $F>10^4\,y/m$[3]. Dispersion and flow porosity of limited importance. Evaluated within the framework of an integrated safety assessment.	FS: – SI: Advantage if a large fraction of the estimated statistical distribution of the flow paths have a transport resistance $F>10^4$ y/m. Unsuitable flow paths can perhaps be avoided later by a suitable choice of repository layout and canister positions. Final judgement is made within the framework of a safety assessment.
Properties "rock matrix" diffusivity D_e and matrix porosity ε_r	Unsuitable if very low diffusivity and matrix porosity (but such conditions are not expected). Evaluated within the framework of an integrated safety assessment.	FS: – SI: Measured values should not be significantly (more than 100 times) lower than the values normally encountered in Swedish crystalline bedrock. Otherwise, special attention is required in the coming safety assessment.

[2] 0.01 m/y is equivalent to approximately $3\cdot10^{-10}$ m/s

[3] 10^4 y/m is equivalent to approximately $3\cdot10^{11}$ s/m

10 Conclusions

This report gives and account of what requirements are made on the rock, what conditions in the rock are advantageous (preferences) and how the fulfilment of requirements and preferences (criteria) is to be judged prior to the selection of sites for a site investigation and during a site investigation. The conclusions and results of the report are based on the knowledge and experience acquired by SKB over many years of research and development. The knowledge gained during SKB's most recent safety assessment, SR 97, is particularly drawn on. The reported requirements, preferences and criteria will be used in SKB's continued work with site selection and site investigations.

The results, and particularly the stipulated criteria, apply to a repository for spent fuel of the KBS-3 type, i.e. a repository where the fuel is contained in copper canisters embedded in bentonite clay at a depth of 400–700 m in the Swedish crystalline basement. If the repository concept is changed or if new technical/scientific findings are made, certain requirements, preferences or criteria may need to be adjusted. It should be emphasized that the work therefore cannot be used as a basis for siting of other types of repositories or in other geological settings.

10.1 Results

10.1.1 What requirements do we make on the rock?

Numerous conditions need to be determined in a site investigation in order to build up a fundamental understanding of the site. But only certain conditions are of direct importance for whether the site is suitable for a repository or the layout of the repository on the investigated site.

The following requirements are made on the rock or the placement of the deep repository in the rock:

- The rock in the repository's deposition zone may not have any ore potential, i.e. may not contain such valuable minerals that it might justify mining at hundreds of metres' depth.
- Regional plastic shear zones shall be avoided if it cannot be demonstrated that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be so-called "tectonic lenses" near regional plastic shear zones where the bedrock is homogeneous and relatively unaffected.
- It must be possible to position the repository with respect to the fracture zones on the site. Deposition tunnels and deposition holes for canisters may not pass through or be positioned too close to major regional and major local fracture zones. Deposition holes may not intersect identified local minor fracture zones.
- The rock's strength, fracture geometry and initial stresses may not be such that large stability problems arise around tunnels or deposition holes within the deposition area. This is checked by means of a mechanical analysis, where the input values comprise the geometry of the tunnels, the strength and deformation properties of the intact rock, the geometry of the fracture system and the initial rock stresses.

- The groundwater at repository level may not contain dissolved oxygen. Absence of oxygen is indicated by a negative Eh, occurrence of Fe(II), or occurrence of sulphide.
- The total salinity (TDS = Total Dissolved Solids) in the groundwater must be less than 100 g/l at repository level.

In addition to the above requirements, there are a large number of preferences, i.e. conditions that are desirable and should be taken into account when positioning the repository in the rock:

- Since it can be difficult to predict how different rocks and minerals will be used in the future, it is preferable to site the deep repository in commonly occurring rock types.
- Moderate density (fracture surface area per volume) of local minor fracture zones is preferable, along with moderate density of fractures.
- It is generally an advantage if the initial rock stresses at the planned repository depth do not deviate from what is normal in Swedish crystalline bedrock.
- It is preferable that the strength and deformation properties of the intact rock be normal for Swedish bedrock, since experience has shown it is possible to carry out rock works with good results in such bedrock.
- It is preferable that the coefficient of thermal expansion have normal values for Swedish bedrock (i.e. within the range 10^{-6} to 10^{-5} K^{-1}) and that it not differ markedly between the rock types in the repository area.
- The rock should have a higher thermal conductivity than 2.5 W/(m,K). Areas with a high potential for geothermal energy extraction should be avoided. The undisturbed temperature at repository depth should be less than 25°C.
- It is an advantage if a large part of the rock mass in the deposition zone has a hydraulic conductivity (K) that is less than 10^{-8} m/s.
- Fracture zones that need to be passed during construction should have such low permeability that they can be passed without problems, which means the zones should have a transmissivity (T) that is lower than 10^{-5} m^2/s and are furthermore not problematical from a construction-related viewpoint.
- It is an advantage if the local hydraulic gradient is lower than 1% at repository level, but lower values do not provide any additional advantage.
- Undisturbed groundwater at repository level should have a pH in the range 6–10, a low concentration of organic compounds ([DOC]<20mg/l), low colloid concentration (lower than 0.5 mg/l), low ammonium concentrations, some content of calcium and magnesium ($[Ca^{2+}]+[Mg^{2+}]>4$ mg/l) and low concentrations of radon and radium.
- It is preferable that it be possible to find canister positions in a large fraction of the rock that have a Darcy velocity lower than 0.01 m/y on a canister hole scale, since lower fluxes increase the retardation of important radionuclides.
- It is preferable that a substantial retardation of important radionuclides take place in the geosphere. A quantitative preference can be expressed in the form of the transport resistance (F parameter), where Darcy velocity, flow distribution and the flow-wetted surface area per volume of rock (or equivalent parameter) are such that a large fraction of all flow paths have F greater than 10^4 y/m.

- It is desirable that matrix diffusivity and matrix porosity not be much lower (by a factor of 100 or more) than the value ranges analyzed in the safety assessment SR 97. The accessible diffusion depth should at least exceed a centimetre or so.
- Areas where biological diversity or species worth protecting may be threatened and areas which are or may be important water sources, soil sources or farmland should be avoided for the deep repository's surface facilities. (Areas protected by law are avoided.)

As a general rule, satisfied preferences lead to greater safety margins, lower costs, simpler investigations or simpler construction of the repository. All preferences do not have to be satisfied for a site to be approved for a deep repository. It may very well be so that "poorer" values for certain parameters are compensated for by "better" values for others. An integrated safety assessment and a construction analysis are therefore always needed to assess safety and performance.

In addition to the above preferences that have directly to do with the properties of the rock, there are preferences that facilitate the characterization of the site. In particular:

- It is preferable that there be a high proportion of exposed rock and otherwise moderate soil depth (preferably less than about 10 m), since this facilitates determination of the lithological and geological-structural conditions in the underlying bedrock from the ground surface.
- It is preferable that the bedrock be homogeneous with few rock types and regular fracturing, although a small-scale variation in mineral composition, for example a gneiss, is no disadvantage.

Even though the requirements and preferences have been formulated on the basis of different safety and construction viewpoints, there is scarcely any example of a conflict between different requirements or preferences. As a rule, conditions that lead to good long-term safety are also advantageous from the construction viewpoint.

10.1.2 Choice of areas for site investigation

Requirements and preferences regarding the rock should of course be used as far as possible to formulate criteria for selection of sites for site investigations. Good knowledge of the conditions on the ground surface usually exists after completion of a feasibility study, while knowledge of conditions in the deep rock is very limited. Criteria can therefore normally only be formulated for the following suitability indicators:

- After completion of a feasibility study, continued studies and investigations are only conducted of areas that are not deemed to have a potential for occurrence of ore or valuable industrial minerals and that are deemed to be homogeneous and to consist of commonly occurring rock types.
- During the feasibility study, the study site is selected and adapted so that a deep repository can be positioned with good margin in relation to regional plastic shear zones and the regional fracture zones interpreted in the feasibility study.
- Areas protected by law are avoided, and areas for further investigations are chosen so that they have few conflicting interests (for example a water source) and so that the surface portion can be adapted with little impact on the near-surface ecosystem.
- Areas with an unsuitably high topographical gradient on a regional scale (greater than 1%) are rejected.

The feasibility studies thus identify areas with a good potential to have suitable conditions. But site investigations (from boreholes) are necessary to check this. At the same time, the report's survey of the generic knowledge of the Swedish crystalline bedrock shows that good prospects should exist to find sites that satisfy all requirements and most of the essential preferences in Sweden.

10.1.3 Under what circumstances should the site investigation be discontinued?

An overall safety assessment and an overall construction analysis comprise essential background material in an integrated assessment of whether a site is suitable. The site is only accepted if it is possible to show in the safety assessment that a safe deep repository can be constructed. During a site investigation, when measurement data have been obtained from repository depth but before the overall assessment has been carried out, criteria are used to check whether the above requirements and preferences may be satisfied. The criteria provide guidance on the outcome of the assessments and can therefore also be used to review a safety assessment.

The following criteria are so important that the site investigation should be discontinued and another site chosen if they cannot be met:

- If large deposits of ore-bearing minerals or valuable industrial minerals are encountered within the repository area, the site should be abandoned.
- During the site investigation, the repository is adapted more precisely to the then-identified fracture zones. Suitable respect distances to major identified regional and local major fracture zones can only be determined site-specifically, but it is assumed that a distance of at least several tens of metres to major local zones and at least 100 metres to regional zones is appropriate. If the repository cannot be positioned in a reasonable manner (if it would have to be split up into a very large number of parts) in relation to regional plastic shear zones, regional fracture zones or local major fracture zones, the site is not suitable for a deep repository.
- If the repository cannot be reasonably configured in such a way that extensive and general stability problems can be avoided, the site is unsuitable and should be abandoned. Extensive problems with "core discing" of drill cores should give rise directly to suspicions that such problems may arise.
- At least one of the indicators negative Eh values, occurrence of Fe^{2+} or occurrence of sulphide must be fulfilled by the results of the measurements of groundwater composition at repository depth. If none of the indicators can clearly indicate the absence of dissolved oxygen, a more thorough chemical assessment is required. If not even these further studies can indicate oxygen-free conditions, the site must be abandoned.
- Measured total salinities (TDS = Total Dissolved Solids) at repository level must be lower than 100 g/l. Occasional higher values can be accepted if it can be shown that the water is located in areas that can be avoided and that the water will not be able to flow to the repository area.

Besides these direct disqualifying criteria, the suitability of the site can be questioned if a large fraction of the rock mass between fracture zones has a hydraulic conductivity greater than 10^{-8} m/s. High permeability of the rock requires local precision adaptation of the repository if the safety margins are to be met.

10.2 Experience from the project work

To give structure to the work, it has been necessary to introduce a rather complicated terminology. The reason for this is that it is vital to be able to differentiate between functions and properties, between requirements and preferences, and between the actual properties of the rock and that which can be determined in various stages of an investigation. The strict nomenclature that has been introduced has been necessary, since it has not always been possible to keep these concepts separate in previous discussions and documents.

The work covers a large number of different disciplines. The properties of the rock can influence numerous different functions. It has therefore been necessary to work in several steps and to go through the factual material in a structured manner with a large number of feedbacks to experts in different disciplines. This structured approach may possibly obscure the fact that only a few of the individual properties of the rock are of great importance for the function of the deep repository. The structured and comprehensive approach has nevertheless been necessary to make sure that important matters and aspects are not overlooked.

The project has striven to describe functions and parameters within various disciplines in a relatively consistent and comprehensible fashion. One problem is that nomenclature and terminology differ slightly between different disciplines. However, the material has been scrutinized and commented on by both internal and external specialists. This recurrent scrutiny has been absolutely necessary.

When it comes to the description of each discipline, the degree of detail may vary. It is also necessary to limit the details in an interdisciplinary study such as this. Hopefully our references will help make the description complete.

In view of the complexity of the work, it has also been deemed necessary to devote a great deal of effort to achieving an internal and external consensus on the work and its results. Requirements, preferences and criteria must not unnecessarily obstruct the flexibility in the continued development and siting work, but must on the other hand be concrete enough to actually provide guidance in the continued work.

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Appendix A

Function tables

Table A-1. Geological conditions that influence the function of the deep repository

Concerned function	Geological conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on canister integrity	Geological stability: Location of regional and local fracture zones See further sections on mechanics, thermalogy, hydraulics, chemistry	Requirements are made in rock mechanics and hydrology.	The canister is emplaced in a stable environment.	Geological-structural model with uncertainties. (Which means that predictability and homogeneity are important).	
Influence on isolating capacity of buffer	See above	See above		See above	
Influence on retarding capacity of rock	See above	See above	See above	See above	
	Ore potential	The waste shall be protected against inadvertent intrusion in conjunction with prospecting		Geological (lithological) model (ore potential, industrial minerals, unusual rock type) Assessment of conflicting interests.	
Construction-related matters	Geological model (rock types and fracture zones)	Safe working environment Environmental impact of investigations and construction work shall be limited and kept within acceptable levels. Construction shall only have a limited and transient impact on the safety functions of the deep repository, and construction and deposition shall be able to proceed simultaneously.	Preference that the deposition area does not have to be split up into a very large number of subareas and that it is possible to position deposition tunnels in a flexible manner in depth in order to obtain a good detailed layout of the repository. The construction work can be carried out with few interruptions and with as little use of extraordinary reinforcement and sealing measures as possible (good constructability).	Rock-mechanical, hydrogeological and thermal analysis of geological model (fracture zones and rock type distribution, dykes and contacts). Repository layout is largely controlled by the geological information. The deposition tunnels avoid major deformation zones in the rock.	

Table A-2. Rock-mechanical conditions that influence the function of the deep repository

Concerned function	Rock-mechanical conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on canister integrity	Deformation of deposition hole	Deformation may not cause canister damage. Means that instantaneous deformation of canister hole <100 mm.		Rock-mechanical analysis model on local scale (configuration of deposition hole, fracture zones, mechanical properties of these and intact rock, density and thermal properties, stress distribution, future loads (rock-mechanical model on larger scale). Seismic analysis.	Börgesson, 1992. SKB, 1999a.
	Seismic events		Consequences of seismic events are analyzed in safety assessment and included in risk estimate.	Statistics on seismic events. Properties of fracture network geometry. Analysis of consequences.	LaPointe et al., 1999
	Lithostatic pressures	The canister may not be damaged if the deposition hole is deformed due to creep.		Function analysis of creep is included in the safety assessment, but does not constitute a ground for requirements on the rock.	SR 97 Main Report, base scenario (SKB, 1999a)
Influence on isolating and retarding capacity of buffer	Deformation of deposition hole	Deformation may not cause serious damage to bentonite.		Rock-mechanical analysis model (see above). Especially analysis of risk of faults (rock-mechanical analysis on larger scale) for different scenarios.	Pusch and Börgesson, 1992
	Overbreak	Extensive overbreak makes deposition hole unusable.	Extensive overbreak may not occur.		
	Fracturing/cavities can influence bentonite erosion	Cavities not so large that bentonite function is lost.		Analysis of largest permissible fracture (combination with hydrological analysis). Requirement probably met if above deformation requirements are met.	
Influence on retarding capacity of rock	Deformation of rock mass and fracture zones leads to changes in permeability.		Negligible changes in relation to other uncertainties.	Rock-mechanical model and analysis of THM consequences.	Hakami et al., 1998

Cont. Table A-2

Concerned function	Rock-mechanical conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Construction-related matters	Overbreak		Minimize the quantity of overbreak.	Rock-mechanical analysis for implemented layout.	
	Stability in tunnels	Extensive stability problems in the deposition area cannot be accepted.		Rock-mechanical analysis for implemented layout.	
	Building costs, reinforcement needs, downtimes. Choice of execution methods etc.		Reasonable building costs and times.	Determined in detailed characterization stage.	

Table A-3. Thermal conditions that influence the function of the deep repository

Concerned function	Thermal conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on canister integrity	Temperature on canister surface influences chemical environment and thereby canister function.	Requirement on maximum temperature on canister surface T<100°C. Layout is determined so that the temperature requirement is met.		Layout is determined so that the temperature requirement is met. The temperature in the near field is determined by layout, thermal conductivity, heat capacity, thermal boundary conditions, bentonite saturation.	Werme, 1998. SR 97 Base scenario.
Influence on isolating and retarding capacity of buffer	Temperature of bentonite influences chemical environment.	Requirement on maximum temperature T<100°C. This requirement is however automatically met if the canister requirement is met.		See above	See above and Bjurström, 1997
Influence on isolating and retarding capacity of rock	Thermomechanical influence – see mechanics table.				
	Potential for geothermal energy can influence the probability of inadvertent intrusion.		The site should not have a special potential for extraction of geothermal energy or storage of same or other energy.	Assessment based on temperature of rock and groundwater and thermal boundary conditions and gradient.	General Siting Study 95.
	Thermal convection. As a rule, the thermal driving force is negligible compared with the topographical one.		Thermal convection may not be an important driving force for groundwater flow – see hydrology. This preference does not lead to any requirements/preferences on the thermal properties of the rock. (The question is primarily of a design/layout character.)	Coupled thermo-hydraulic groundwater model (thermal conductivity, heat capacity, thermal boundary conditions, groundwater model with density-dependent flow, see hydrology).	Thunvik and Braester, 1980. Thunvik and Braester, 1991.
Biosphere-related matters	Decay heat of waste influences ground temperature.			Completed analyses show that the influence is negligible.	SR 97 (Base scenario)
Construction-related matters	Temperature on repository scale	Layout is determined so that temperature requirement (as above) is met.	Preference that canisters do not need to be spread out over large volumes to meet temperature requirement.	Temperature in near field (layout, thermal conductivity, heat capacity, thermal boundary conditions).	

Table A-4. Hydrogeological conditions that influence the function of the deep repository

Concerned function	Hydrogeological conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on canister integrity	Influence of groundwater flow on groundwater chemistry		Water with unsuitable composition should not be able to flow to the deposition area. (For certain scenarios, this can be accepted for a brief time.)	Model of regional groundwater flow (regional hydrology, large fracture zones, permeability of rock mass, topography...). Identification of water with unsuitable composition (see chemistry).	Svensson, 1999
	Influx of corrodants (groundwater flow on deposition hole scale)		Preference of low groundwater flow on canister scale (can however easily be replaced by conservative assumption in SA).	Model of local groundwater flow (permeability, regional groundwater flow)	Approximate calculations of canister corrosion are made within SR 97.
	Groundwater pressure	The canister may not collapse due to high hydrostatic pressures		Hydrostatic pressure is determined by repository depth and future scenarios. The canister can easily withstand an ice cover 3,000 m thick	Werme, 1998. Börgesson and Hernelind, 1998. SR 97
Influence on isolating and retarding capacity of buffer	Flow in near field influences wetting and swelling. Swelling can affect the canister.	No requirements. Analysis by Werme, 1998 and SR 97 (Börgesson and Hernelind, 1998) shows that the canister can withstand very uneven swelling	Evenly distributed flows is an advantage.	Model of local groundwater flow (permeability, regional groundwater flow). Model for bentonite wetting, design of canister and repository.	Werme, 1998 Börgesson and Hernelind, 1998
	Flow in rock influences water saturation of the bentonite.		The bentonite's water saturation should be sufficient, otherwise its thermal conductivity will be insufficient, requiring a change in the layout of the repository.	See above. The preference could entail a preference for minimum water flow in the deposition holes, but any problems can be solved artificially.	Börgesson, 1992, SR 97 base scenario page 137
	Flow in near field influences wetting and swelling.		Bentonite shall function as a diffusion barrier.	See above	

Cont. Table A-4

Concerned function	Hydrogeological conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on retarding capacity of rock	The groundwater flow around the deposition hole influences the retardation in the bentonite/rock transition.		Preference of high resistance (low groundwater flows)	Model of local groundwater flow (see above) and transport model	Moreno and Gylling, 1998
	The groundwater flow influences the retention capacity of the rock.		No absolute requirements, but sufficient to provide barrier function – shall at least suffice to provide safety in total SA.	Permeability, flow paths and flow-wetted surface area	Andersson et al., 1998b
Biosphere-related matters	Impact on ecosystems	Avoid areas protected by law.	Very little impact on ecosystems during construction, operation and post-closure	Regional groundwater flow, influence of grouting, groundwater lowering. Description of ecosystems etc.	
	Natural resources		Avoid valuable natural resources	Survey of natural resources etc.	
Construction-related matters	Water seepage and grouting needs		Moderate water seepage, or areas with excessive seepage can be sealed with reasonable grouting measures (grouting needs), since this influences costs and building times.	Calculated flows for given (or alternative) repository layout (groundwater model as above). Layout is controlled so that the groundwater flow in the deposition area is low by avoiding regional and local major fracture zones.	
			See above	See above	
	See above	The grouting needs may not be so great that there is a risk of serious environmental impact or adverse impact on the composition of the groundwater in the deep repository			
	See above		From an occupational safety viewpoint, the probability of heavy water seepage/collapse must be small, but problems can always be managed with increased costs as a consequence.	See above	

Table A-5. Chemical conditions that influence the function of the deep repository

Concerned function	Chemical conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on canister integrity	Redox conditions and presence of substances that influence canister corrosion	No dissolved oxygen may be present in the groundwater. (Indicated by Eh<0, Fe^{2+} or HS^- in the water.)	Preferable with low concentrations of substances that influence copper corrosion, such as sulphide, ammonium, nitrite, nitrate and total salinity.	• Geochemical model (water samples, mineralogy, regional groundwater flow). • Assessment of risk of transport of water with unsuitable composition (see transport and hydrogeology) • (Models of canister corrosion are assumed to be developed outside of the site investigation) • Assessment of biological activity (transformation of sulphate to sulphide). Parameters: Eh, Fe^{2+}, HS^-, Cl^-, NO_2^-, NO_3^-, NH_4^+, (pH, SO_4^{2-}, DOC, dissolved gases (i.e H_2 and CH_4, HPO_4^{2-}, HCO_3^-, bacteria)	Copper corrosion is discussed in SKB TR 92-26, Werme et al., 1992, Wersin et al., 1994, SR 97 Base scenario, Saario et al., 1999. Ahonen, 1999.
Influence on isolating and retarding capacity of buffer	Presence of substances that influence bentonite stability, different ions and total salinity.	The buffer's swelling pressure must be preserved ([TDS] <100 g/l).	Show that the clay gel does not erode and form colloids. $[Ca^{2+}]+[Mg^{2+}]>4$ mg/l	Function analyses, see above. Parameters: Na^+, Ca^{2+}, Mg^{2+}, TDS, (pH, Al^{3+}, SiO_3^{2-}).	For [TDS] see Karnland (1997) and SR 97 Main Report section 8.9.3. For Ca^{2+} och Mg^{2+} see further Laaksoharju et al., 1995.
Influence on release of nuclides to groundwater	Groundwater composition influences fuel transformation.		The model for fuel dissolution presumes reducing conditions.	See SR 97 Canister defect scenario	SR 97 Canister defect scenario
	Groundwater composition influences nuclide solubility		Preference regarding composition is set so that the solubilities are not appreciably higher than the values used in the SR 97 safety assessment.	Solubility calculations with "equilibrium codes". Thermodynamic data, groundwater composition.	Bruno et al., 1997. SR 97

Cont. Table A-5

Concerned function	Chemical conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on retardation in the geosphere	Colloids, bacteria, dissolved gases, redox conditions, pH, complexing agents, mineralogy		Good sorption capacity, little complexation and negligible colloid transport. Not appreciably poorer conditions than those used in SR 97.	Sorption values are determined by groundwater chemistry. Parameters: mainly pH, Eh, TDS, etc.	Carbol and Engkvist, 1997. SR 97.
Biosphere-related matters	Near-surface groundwater chemistry			Knowledge of the composition of the near-surface ground-water is needed to describe the near-surface ecosystems. This knowledge is also important to show whether more recently discovered changes are caused by the repository or are a consequence of the "natural" evolution of conditions.	
Construction-related matters	Working environment		Concentrations of substances that are dangerous from an occupational health viewpoint (e.g. radon) must be kept below limit values. (This can as a rule always be achieved by e.g. good ventilation.) It is preferable that small or no design or layout measures are needed to ensure a chemically good working environment.	If preferences cannot be met, function analyses as described above are needed. Requirements and preferences can however almost always be met by means of a suitable layout of the repository.	
	Environmental impact of construction	Limited environmental impact of investigations and construction is a requirement			

Table A-6. Transport conditions that influence the function of the deep repository

Concerned function	Transport conditions that influence function	Requirements	Preferences	Function analysis and concerned parameters	References
Influence on integrity of canister and buffer	Influx of oxygen and other corrodants. Influx of substances that can influence the buffer.	No continuous influx of water with dissolved oxygen. Limited influx for brief time is acceptable.	Limited influx of corrodants	Analysis of mass transport and corrosion process. (See also hydrology and chemistry) Model of local groundwater flow (see hydrology, chemistry and fracture aperture in deposition hole.) Analysis of retention properties for flow paths from areas with unsuitable water chemistry (flow paths, groundwater flow, flow-wetted surface area, rock matrix properties). See also hydrology and chemistry.	SR 97 Guimera et al., 1999, SR 97 glaciation scenario
Influence on retarding capacity of geosphere	Retardation in bentonite/rock and tunnel/rock transition		Preference for retardation in buffer/rock transition.	Analysis of near-field transport in rock (groundwater flux and local fracture geometry)	See in particular the rock description in the near-field transport model COMP23. (Moreno and Gylling, 1998)
	Retention capacity of far-field rock		High transport resistance in the geosphere ($F>10^4$ y/m).	Transport resistance ("F parameter"), which is dependent on groundwater flow, flow paths and flow-wetted surface area. Sorption data, matrix diffusivity and matrix porosity.	Flow-wetted surface area: Andersson et al., 1998b; SR 97, 1999 canister defect scenario. See also hydrology and Carbol and Engkvist, 1997.

Appendix B

Parameter tables

Table B-1. Suitability indicators for geology

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Regional topographical gradient	Retardation, rock		Important basic information	RD&D-Programme 95 (SKB, 1995a): Within the interval 0.1–1% on a regional scale	No, not directly	–
Soils	None, the parameter influences predictability		Preference for thin soil layer and high proportion of exposed rock	Varies	No, no specific requirements or preferences	FS: – SI: Not relevant after site investigation
Rock types	Retardation, rock Isolation, intrusion, occupational safety	That the rock types in the deposition area do not have ore potential and do not contain such valuable minerals as to justify mining at a depth of hundreds of metres.	Preference that there is no occurrence of valuable utility stone or industrial minerals. Preference for common rock type. (Indirect requirements/preferences from rock mechanics and hydrogeology). Avoid rock types that emit much radon.	Varies in Sweden	Yes	FS: Avoid areas with known ore potential and heterogeneous or unusual bedrock. SI: Local adaptation of repository with reference to indicator. If extensive occurrence of ore-bearing minerals is encountered, the site should be abandoned.
Plastic shear zones	Isolation canister, bentonite and rock Retardation, rock	Regional plastic shear zones are avoided, if it cannot be shown that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be tectonic lenses near regional plastic shear zone that can be suitable for a deep repository.		See regional general siting studies.	Yes, if sufficient repository volume cannot be obtained the site is unsuitable.	FS: Avoid known regional plastic shear zones. If sufficient repository volume cannot be obtained, another area must be chosen. SI: Revise layout according to new knowledge. If the repository cannot be positioned in a reasonable manner (if it would have to split up into a very large number of parts), another area must be chosen.

Cont. Table B-1

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Fracture zones	Isolation canister, bentonite and rock Retardation, rock	Deposition tunnels and holes may not pass through or be located near regional and local major fracture zones. Assumed respect distances will be used in conjunction with the stepwise site investigation and the design process. But the real distances that are needed are determined via a site-specific function analysis.	Deposition holes should not intersect identified local minor fracture zones. Moderate densities (fracture surface area per volume) of fractures and of local minor fracture zones.	See regional general siting studies.	Yes, if sufficient repository volume cannot be obtained the site is unsuitable.	FS: Choose area for continued studies so that a deep repository can be positioned with good margin in relation to the fracture zones identified in the feasibility study. If the repository cannot be positioned in a reasonable manner, another area must be chosen. SI: Suitable respect distances to identified regional and local major fracture zones can only be determined site-specifically but are assumed to comprise at least several tens of metres to local major zones and at least 100 metres to regional zones. If the repository cannot be positioned in a reasonable manner (would have to be split up into a very large number of parts) in relation to plastic shear zones, regional fracture zones or local major fracture zones, the site is not suitable for a deep repository.

Table B-2. Suitability indicators for rock mechanics

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Initial rock stresses	Design layout Design construction analysis Isolation, rock Retardation, rock Design working environment	Extensive spalling or other extensive overbreak may not occur within a large portion of the deposition area. Function is verified by means of a site-specific analysis.	Normal (considerably lower than 70 MPa) at repository depth.	The vertical stress is linearly dependent on the depth (14 MPa at 500 m). The greatest horizontal stress at this depth is normally greater and lies in the range 10–70 MPa.	Yes	FS: No criteria. SI: Calculated stress situation in the rock nearest the tunnels and the resultant rock stability during and after the construction phase is used mainly to adapt repository depth and layout. If the repository cannot be reasonably configured in such a way that extensive and general stability problems can be avoided, the site is unsuitable and should be abandoned. Extensive problems with "core discing" should directly give rise to the suspicion that problems may be encountered with spalling during tunnelling.
Intact rock (E, ν, compressive strength etc.)	Isolation, canister and rock engineering	Extensive spalling or other extensive overbreak may not occur within a large portion of the deposition area.	It is preferable that the intact rock have strength and deformation properties that are normal for Swedish bedrock.	E: 5–100 GPa ν: 0.15–0.3 Compressive strength 50–250 MPa Tensile strength 2–10 MPa (Stille and Nord, 1990)	Yes (compressive strength), although the parameter cannot be used in isolation but is included in a mechanical analysis (see criteria).	FS: Assessment based on preliminary rock type forecast may not indicate unfavourable conditions. SI: Special attention if the strength of the rocks deviates from normal values in Swedish bedrock. See also "initial rock stresses".
Fractures and fracture zones	Isolation/canister Retardation rock Design	For adaptation to geometry of fracture zones and fractures – see "geology".	For adaptation to geometry of fracture zones and fractures – see "geology". Tunnel layout/location is chosen based on stresses and fracture directions. Large friction angle suitable.	Stille and Nord (1990)	Yes (geometry).	FS: For adaptation to geometry of fracture zones and fractures – see "geology". SI: For adaptation to geometry of fracture zones and fracture – see "geology". Rock-mechanical analysis of function.

Cont. Table B-2

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Rock mass strength	Design layout Design construction analysis		Properties at least on a par with normal conditions in Swedish bedrock.	Normally good constructability	Yes	FS: No criteria. SI: The forecast of the properties of the rock mass that is made in conjunction with the site investigation is used for repository layout and the constructability forecast. The constructability forecast is included in the total comparison material between sites, but has no direct safety-related importance. Good constructability is of course advantageous.
Coefficient of thermal expansion α	Isolation, rock Retardation, rock		Normal values for Swedish bedrock. Not too inhomogeneous.	$3 \cdot 10^{-6}$ K^{-1} $<\alpha<1.5 \cdot 10^{-5}$ K^{-1}	Not primary, but needs to be determined	FS: No criteria. SI: Assessment of inhomogeneities – if very inhomogeneous, broader analysis of consequences is needed. Choice of deposition holes made during repository construction.
Future loads (seismicity, glaciation...)	Isolation, rock Retardation, rock			See SR 97	No	Future loads are analyzed within the framework of the scenario analysis in a safety assessment. No ground for site-specific differences.

Table B-3. Suitability indicators for thermal properties

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Thermal conductivity λ and heat capacity c of rock mass	Isolation, rock Retardation, rock		Good thermal conductivity (influences repository layout, repository size). $\lambda > 2.5$ $Wm^{-1}K^{-1}$	Basic rock types: 1.7 $Wm^{-1}K^{-1} < \lambda < 3.6$ $Wm^{-1}K^{-1}$. Rock types with intermediate composition: 2.2 $W.m^{-1}K^{-1} < \lambda < 4.2$ $Wm^{-1}K^{-1}$. Granitoid rock types: 2.5 $Wm^{-1}K^{-1} < \lambda < 5.5$ $Wm^{-1}K^{-1}$. SGU: Sundberg, 1995 and Sundberg, 1988	Yes	FS: If an assessment is made (from rock types) that thermal conductivity is below the preferred value, the size of the area that must be studied is affected. SI: Detailed knowledge of rock types and thermal conductivity is used to adapt the repository layout. However, Thermal conductivity only has to be taken into account if there is a risk that it is below the preferred level (2.5 Wm^{-1} K^{-1}).
Ambient temperature (initial, external temperature, geothermal gradient)	Isolation, rock Retardation, rock	Areas with potential for geothermal energy extraction (very high geothermal gradient) should be avoided.	Temperature at repository depth $< 25°C$	At 500 m depth: Initial condition: $7°C < T_{500} < 18°C$ Thermal gradient: 10–15 Kkm^{-1} Sundberg, 1995	Yes	FS: Avoid areas with assessed large potential for geothermal energy extraction. If the initial temperature is judged to exceed the maximum preferred, it must be taken into account in the choice of how large an area needs to be investigated. SI: Like FS. The initial temperature must be taken into consideration in determining the repository layout if it is above or near the maximum preferred.

Table B-4. Suitability indicators for hydrogeology

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Permeability for fracture zones and fractures	Isolation, bentonite Retardation, bentonite Isolation, rock Retardation, rock	For adaptation to geometry of fracture zones and fractures – see geology.	It is an advantage if a large portion of the rock mass in the deposition area has $K<10^{-8}$ m/s (on deposition hole scale). Integrated function analysis is needed. Zones that need to be passed during construction should have such low permeability that passage can take place without problems. (Zones with $T<10^{-5}$ m²/s or zones that are not difficult from a construction point of view.)	Transmissivity of fracture zones: $1.5 \cdot 10^{-5}$ m/s – $2 \cdot 10^{-10}$ m/s. Hydraulic conductivity of the rock mass (on 30 m scale) 10^{-6} m/s and 10^{-12} m/s Walker et al., 1997.	No, not when it comes to regional and local fracture zones (must be avoided anyway). Yes, when it comes to that portion of the rock that contains local minor fracture zones and discrete fractures.	FS: No criteria. For adaptation to geometry of fracture zones and fractures – see geology. SI: A large portion of interpreted K values in the rock mass are $K<10^{-8}$ m/s. (Otherwise need for local detailed adaptation if the safety margin is to be met.) Fracture zones that need to be passed during construction should have an interpreted transmissivity of $T< 10^{-5}$ m²/s and lack clay filling (otherwise increased attention to grouting and other construction analysis).
Flow porosity and storage coefficient			No, since the parameters do not influence retardation of sorbing substances or long-lived non-sorbing substances (see transport).		No, has little importance for function	
Flow porosity ε_f	Isolation, rock Retardation, rock			$10^{-3} < \varepsilon_f < 10^{-2}$ Rhén (ed), 1992, Winberg (ed), 1996, and Rhén (ed), 1997	No	
Storage coefficient S_s	Understanding			10^{-7} m^{-1} $<S_s<10^{-5}$ m^{-1} Rhén (ed), 1992, Winberg (ed), 1996, and Rhén (ed), 1997	No	

Cont. Table B-4

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Groundwater properties			Should be known and taken into account in groundwater modelling			
Density ρ	Isolation, rock Retardation, rock			ρ is determined by prevailing temperature and salinity (TDS) and by fundamental properties of water. Rhén (ed), 1997, Probert and Claesson, 1997.	No, but the parameter is very important to know	
Viscosity ν	Isolation, rock Retardation, rock			ν is determined by prevailing temperature and salinity (TDS) and by fundamental properties of water. Rhén (ed), 1997, Probert and Claesson, 1997.	No	
Near-surface ecosystems	Biosphere	No geoscientific requirements. Areas protected by law are avoided. The repository's isolating and retarding function shall in any case be so good that adequate safety can be achieved regardless of what ground conditions prevail.	Avoid areas for the deep repository's surface facilities where biological diversity and species worth protecting can be threatened and areas that are or may be important water sources, soil sources or farmland. Data on the near-surface ecosystems are primarily valuable for building up a credible model description. Good access to such data of high quality increases the credibility of the modelling.	Not applicable	Yes	FS: Areas protected by law shall be avoided. It is a preference that areas of interest for site investigations have few competing interests and that the surface facilities can be preliminarily adapted so that there is little impact on the near-surface ecosystem. SI: Criteria as above.

Cont. Table B-4

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Boundary conditions and supporting data					Data are primarily needed to build up credible system descriptions.	
Hydraulic gradient (and pressure)	Isolation, canister Retardation, rock		Local gradient <1% at repository level (no advantage if even lower). Take salinity into account.	0.05% till 0.6% for sites analyzed in SR 97	Data are not primarily useful as suitability indicators, but rather are needed to build up credible groundwater models.	FS: Areas with an unsuitably high gradient are screened out. SI: Gradient can be used in determination of boundary conditions for modelling.
Recharge/discharge	Retardation, rock		Advantage if long distance to discharge area (but retardation is determined mainly by the properties of the rock).		See "gradient"	FS: – SI: Assessment of location included in safety assessment.
Shoreline displacement	Retardation, rock		No preferences, but must be taken into account in modelling		See "gradient"	

Table B-5. Suitability indicators for chemistry (groundwater composition)

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Occurrence of dissolved oxygen	Isolation, canister Retardation, fuel Retardation, bentonite Retardation, rock	Absence of dissolved oxygen at repository level (indicated by negative Eh, occurrence of Fe(II) or occurrence of sulphide).		At repository depth the Eh values are negative, [Fe^{2+}] 5 µg/l – 10 mg/l sulphide conc.: 0.01 – 5 mg/l. Laaksoharju et al., 1993, 1998)	Yes	FS: No criteria (no data available) but there is no reason to believe that the requirement cannot be met. SI: At least one of the indicators Eh, Fe^{2+}, HS^{-} must be satisfied.
pH	Isolation, canister Isolation, bentonite Retardation, fuel Retardation, bentonite Retardation, rock		Undisturbed groundwater at repository level should have a pH in the range 6–10.	Below depths of 100 m, pH is as a rule 6<pH<10, but deviations (e.g. Stripa) occur. (Laaksoharju et al., 1993, 1998) Above 100 m the expected range is greater.	Yes	FS: No criteria (no coupling to surface water). SI: Below the –100 m level, quality-approved values should lie in the range 6–10.
TDS (Total Dissolved Solids)	Isolation, canister Isolation, bentonite Retardation, bentonite Recipient	TDS<100 g/l		Down to a depth of 1,000 m 0–35 g/l. Up to 100 g/l has been measured at 1,700 m depth (Laxemar). Depth to high TDS generally greater at inland locations. (Laaksoharju et al., 1993, 1998).	Yes	FS: No criteria SI: Quality-approved measured TDS at repository level must meet this requirement. Occasional higher values can be accepted if it can be shown that the water is located in areas that can be avoided.
DOC (Dissolved Organic Carbons)	Isolation, canister Isolation, bentonite Retardation, fuel Retardation, bentonite Retardation, rock			As a rule, [DOC]<10 mg/l at repository level. Higher values can occur temporarily during the construction period.	No	FS: No criteria SI: Attention if very high concentrations are measured.

Cont. Table B-5

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
NH_4 (ammonium)	Isolation, canister		Low concentrations		No	FS: No criteria SI: Attention if very high concentrations are measured.
Ca and Mg	Isolation, bentonite Retardation, bentonite Retardation, rock		$[Ca^{2+}]+[Mg^{2+}]>4$ mg/l at repository depth to ensure that the bentonite gels stably and does not create colloids (Laaksoharju et al., 1995). Higher values no advantage.	[Ca] in range 21–1,890 mg/l and [Mg] in range 1–110 mg/l (Laaksoharju et al., 1993, 1998). (I.e. preference always satisfied).	Yes	FS: No criteria SI: Special investigation required if measured concentrations deviate from preferences.
Colloids	Retardation, rock		Low conc. <0.5 mg/l	Median concentration of colloids in the groundwater is less than 0.05 mg/l (Laaksoharju et al., 1995).	Doubtful (preference carries little weight).	FS: No criteria SI: Attention if very high concentrations (see preferences) are measured.
Free gas	Isolation, canister Retardation, rock		Not free gas form at repository depth	Does not exist as a rule.	No	FS: No SI: Attention if very high concentrations are measured.
Ra, Rn	Working environment		Low concentrations		No, high concentrations can be managed by ventilation etc.	
Other components	Understanding					

Table B-6. Suitability indicators for transport properties of the rock

Geoscientific parameter	Reference to function in function table	Requirements regarding parameter	Preferences regarding parameter	Value range in Swedish crystalline bedrock	Possible suitability indicator	Criteria after feasibility study (FS) and after site investigation (SI)
Groundwater flux (Darcy velocity) on canister scale and the total fracture aperture	Isolation, bentonite Retardation, bentonite	The flow and the apertures are not so large that the bentonite is damaged. (Can scarcely occur and can always be avoided.)	Low water flux and small apertures (Darcy velocity on deposition hole scale lower than 0.01 m/y). Final judgement in safety assessment.	Darcy velocity between 10^{-5} m/y – 10^{-1} m/y.	Yes	FS: – SI: Advantage if the estimated Darcy velocity (on a scale of 10 m) is lower than 0.01 m/y for a large number of positions in the rock. Final judgement is made within the framework of a safety assessment.
Transport resistance F $F = a_r \cdot L/q$ where a_r = flow-wetted surface area per volume of rock L = length of streamtube q = Darcy velocity	Retardation, rock		Substantial retardation an advantage. This is achieved in flow paths where $F > 10^4$ y/m	$8 \cdot 10^2$ y/m $< F < 2 \cdot 10^6$ y/m (Andersson, 1999)	Yes	FS: – SI: Advantage if a large fraction of the estimated statistical distribution of the flow paths have a transport resistance $F > 10^4$ y/m. Unsuitable flow paths could perhaps be avoided later by a suitable choice of repository layout and canister positions. Final judgement is made within the framework of a safety assessment.
Rock mass sorption coefficient K_d, matrix diffusivity De and matrix porosity ε_r	Retardation, rock		It is advantageous if matrix diffusivity and matrix porosity are not much lower than the value ranges analyzed in the safety assessment SR 97 (see Ohlsson and Neretnieks, 1997). The accessible diffusion depth should at least exceed a centimetre or so.	The sorption coefficient K_d and matrix diffusivity of the rock mass are nuclide-specific and dependent on groundwater chemistry (see Carbol and Engkvist, 1997 for K_d and Ohlsson and Neretnieks, 1997 for diffusivities and porosities).	Yes	FS: – SI: Measured values should not be significantly more than 100 times lower than the values normally encountered in Swedish crystalline bedrock. Otherwise, special attention is required in the coming safety assessment.

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