Technical Report

TR-00-20

Geoscientific programme for investigation and evaluation of sites for the deep repository

Svensk Kärnbränslehantering AB

August 2000

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Keywords: deep repository, spent nuclear fuel, site evaluation, safety assessment, design, site investigations, boreholes.

Preface

The work of producing the material on which the siting of the deep repository for spent nuclear fuel is based is proceeding in two stages: feasibility studies and site investigations. The feasibility study stage is now being brought to a conclusion and has yielded a broad body of data for the continued work. The goal for the upcoming site investigation phase is to obtain the permits required to site and build the deep repository. The principal task for SKB is to compile all the supporting material required for this. This task includes investigating the bedrock and other conditions on selected sites in order to establish whether these sites are suitable for a deep repository.

The programme for the site investigation phase in a municipality must be tailored to the specific conditions on the site in question, in the municipality and in the region. SKB plans to present a comprehensive picture of the programmes for the site investigation phase in the upcoming supplement to RD&D-Programme 98. The intention is to describe planned activities with regard to:

- the bedrock, long-term safety and the rock excavation technology,
- the industrial establishment and associated questions concerning land use, transport, infrastructure and environmental aspects,
- societal aspects and public opinion, including the impact of the establishment on the local business community, labour market and other conditions.

This report presents SKB's programme for investigation and evaluation of sites for the deep repository. The emphasis is on methodology and technology for investigating and evaluating the rock, but surface ecosystems and other conditions at the surface are also discussed. The purpose of the report is to satisfy the requirements on "a well-defined site investigation programme" in accordance with the Government's decision of 24 January 2000 on RD&D-Programme 98. The programme that is presented is general. It will comprise a basis for planning corresponding activities at a later stage, tailored to the specific conditions in the municipalities and on the sites selected.

The work has been carried out by a group consisting of Karl-Erik Almén, Johan Andersson, Rolf Christiansson, Sven Follin, Allan Hedin, Stig Pettersson, Jan-Olof Selroos and the undersigned.

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Summary

SKB's goal is to be able to commence site investigations in 2002. Extensive preparations are now being made for this transition to the next phase in the siting process for the deep repository.

Premises

One of the principal tasks assigned to SKB is to develop a distinct site investigation programme. By "site investigation programme" is meant here a primarily *geoscientific programme for investigation and evaluation of sites*. 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's suitability for a deep repository. This report describes the investigation and evaluation programme, which is focused on a deep repository in accordance with the KBS-3 method for spent nuclear fuel.

The programme is general and will later be augmented with more detailed technical descriptions. When areas for site investigations have been chosen, the programmes will be adapted to the site-specific conditions.

Goal and stages

The goal of the site investigation phase is to obtain the permits that are required to site and build the deep repository. The geoscientific work during the site investigation phase is supposed to provide the broad knowledge base that is required to evaluate the suitability of investigated sites for a deep repository. The material must be comprehensive enough to

- show whether the selected site satisfies fundamental safety requirements and whether civil engineering prerequisites are met,
- permit comparisons with other investigated sites, and
- serve as a basis for adaptation of the deep repository to the properties and characteristics of the site with an acceptable impact on society and the environment.

The work is being carried out in consultation with municipalities, regulatory authorities and nearby residents.

When investigations and other studies have been completed and the results analyzed, SKB will decide whether the necessary conditions have been fulfilled for submitting an application for a permit for siting of the deep repository on one of the sites. If so, the application will be submitted along with the environmental impact statements that have been prepared in consultation with all concerned parties. Permit and permissibility review will then take place under the Nuclear Activities Act, the Environmental Code and the Planning and Building Act. If a permit is obtained, the detailed characterization phase will commence.

The point of departure for the site investigations are candidate areas in feasibility study municipalities. A candidate area is a geographic area that has been deemed suitable for further studies based on data from the feasibility study phase. The size of the candidate areas is dependent on how precisely a possible siting of the deep repository has been able to be fixed, but it can be up to a couple of hundred square kilometres. In other words, the preconditions in the selected candidate areas are not equal as regards the size of the area of interest and knowledge of the geological conditions. The first task will therefore be to bring the areas up to a comparable knowledge level, define a priority site within each area for further in-depth investigations, and acquire preliminary knowledge on the rock conditions at repository depth on these sites. This stage is called *initial site investigation*. By "site" is meant the area required to accommodate and characterize a deep repository and its immediate environs, roughly 5–10 square kilometres.

The main purpose of the initial stage is:

- to identify and select the site within a specified candidate area that is deemed to be most suitable for a deep repository and thereby also the part to which further investigations will be concentrated, and
- to determine, with limited efforts, whether the feasibility study's judgement of the suitability of the candidate area holds up in the light of in-depth data.

If the overall assessment shows that the prospects for siting a deep repository on the investigated sites are still good, *complete site investigations* follow on these sites. The purpose of the complete site investigations is to gather the material that is required to select a site and apply for a permit for siting of the deep repository. This means that knowledge of the rock and its properties needs to be increased so that:

- a geoscientific understanding of the site can be obtained as regards current states and naturally ongoing processes,
- a site-adapted repository layout can be arrived at,
- an analysis of the feasibility and consequences of the construction project can be done, and
- a safety assessment can be carried out to determine whether long-term safety can be ensured on the site.

Activities during the site investigations

The work during the site investigation phase is planned so that a body of knowledge is progressively built up that can serve as a basis for comparison between the sites. The emphasis in the work will naturally lie on investigations of the rock, since it is there the lack of knowledge is greatest today. On the basis of the site-specific information, the principal activity *investigations* sets up geoscientific models (descriptions) of the site. *Design* uses these models to produce a site-specific facility description with repository layout and assesses the consequences of the construction work. *Safety assessment* evaluates long-term safety based on specified site models and repository layout. The body of knowledge on the site evolves gradually, so that the various analyses of the site must also be done in stages. Results of previous analyses may also be used to narrow down the focus of the investigation activities in later stages. The different principal activities must therefore interact. This report focuses primarily on these three technical principal activities.

The main product of the investigations is a *site description*, which presents collected data and interpreted parameters that are of importance both for the overall scientific understanding of the site and for the analyses and assessments that are made of design and safety assessment with respect to the deep repository's layout and construction as well as its long-term performance and radiological safety. The information is collected in a database. The site description should furthermore present an integrated description of the site (geosphere and biosphere) and its regional environs with respect to current state and naturally ongoing processes.

The main product of design is a *facility description*, which presents layout proposals with associated construction analyses based on data reported from investigations. A technical risk evaluation is carried out, by which is meant a description of uncertainties in calculations and the environmental impact of the civil engineering work. The facility description includes the choice of technology and repository layout, plus an establishment description.

The main product of the safety assessment is a *safety report*, which analyzes whether long-term safety is ensured for the planned deep repository based on reported investigation results and the proposed repository layout. The safety assessment includes analyses of technical, hydraulic, mechanical and chemical processes around a deep repository as well as calculations of radionuclide transport. Data after completed site investigation should serve as a basis for an assessment of at least the same scope as the SR 97 safety assessment. The methodology in SR 97 hereby comprises a basis for the methodology to be used in future safety assessments.

Field activities and environmental considerations

The field work required during the site investigation will vary from site to site. This is particularly true during the initial phase of the site investigation, since the preconditions in the selected candidate areas are not equal as regards the size of the area of interest and knowledge of the geological conditions. The need for data is the primary factor that will guide field activities during the site investigations. What is possible and suitable to do is, however, also determined to a great extent by environmental conditions on the site.

Measurements will be made from the air, from the ground and in boreholes. To enable the measurements to be performed quickly and conveniently, some small roads may have to be built and power lines run up to the drilling sites. Drilling is the "heaviest" activity during the site investigations. Two main types of holes are drilled: cored boreholes and percussion boreholes. The deeper cored boreholes are drilled with bigger machines, but are limited to no more than 20 or so drilling sites with a duration of a few months per site. Three to four drilling machines will probably be operating simultaneously within the study site.

A site investigation cannot be compared directly to an ordinary construction or civil engineering project. Even though the investigated surface area is large, field activities are mainly concentrated to individual measurement sites within the area. Investigations will also be conducted in a larger surrounding area, but only to a limited extent.

The activities will be adapted to the natural and cultural values of the site so that the impact is limited. The description provided in this report cannot be very detailed, since it is not based on a real site. Exactly how the activities will be adapted to conditions on a real site will therefore be discussed in the site-specific programmes that will be presented on a later occasion. For this work, SKB will consult with the concerned municipalities and landowners. Similarly, organizations and private persons with specialized local expertise concerning e.g. the study site's natural and cultural values will be consulted.

Protected areas will be avoided wherever possible. The same applies to other areas that may be sensitive to disturbances, such as breeding areas for unusual bird species and localities with rare plants. With good knowledge concerning the study site's flora and fauna, the field activities can be adapted so that any disturbances will be limited. This can be achieved without compromising the quality of the investigation results, although the investigations may in some cases take longer for this reason.

Timetable

The initial site investigations are estimated to take around 2 years. The time required is projected to be different for the different sites because the conditions and level of knowledge are different. To enable the resources to be utilized efficiently, the timetables for the investigations at the different sites will be somewhat staggered.

The complete site investigations include several drilling stages, where 3–4 deep core boreholes are drilled simultaneously. This is followed by measurements and evaluation of the results. Each drilling stage is estimated to take around one year. After the last drilling stage, a summarizing and comparative evaluation of the different sites is carried out and a permit application with underlying documentation is prepared. This means that the duration of the complete site investigations can be estimated at 3½–4 years.

An application for siting and construction of the deep repository on one of the investigated sites will be submitted to the Government under the Nuclear Activities Act and the Environmental Court under the Environmental Code. The supporting documentation will then be examined by the authorities and the application reviewed by the Environmental Court. The time required for this is difficult to predict, but is estimated at about two years, which means that the site investigation phase in its entirety is projected to last about 7–8 years.

Contents

1 Introduction

SKB's goal is to be able to commence site investigations in 2002. Extensive preparations are now being made for this transition to the next phase in the siting process for the deep repository.

1.1 Purpose

One of the principal tasks assigned to SKB is to develop a distinct site investigation programme. By "site investigation programme" is meant here a primarily *geoscientific programme for investigation and evaluation of sites*. 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's suitability for a deep repository. This report describes the investigation and evaluation programme.

The programme is general and will later be augmented with more detailed investigation programmes. When areas for site investigations have been chosen, the programmes will be adapted to the site-specific conditions. The programme hierarchy is described in greater detail in section 1.3.

1.2 Background

SKB is responsible for managing Sweden's nuclear waste and developing a method and site for its final disposal. Before the Government can review and approve an application for a siting permit for the deep repository, SKB must have carried out general siting studies, feasibility studies and site investigations to assemble the necessary supporting documentation for such a decision, see Figure 1-1.

General siting studies are regional (county) or nationwide compilations and analyses of existing data that can be of interest for judging siting prospects in different parts of Sweden.

Feasibility studies are compilations and analyses on a municipal scale. As in the general siting studies, existing information is compiled, but the feasibility studies are performed on a more detailed scale. Besides information on the bedrock, the feasibility studies also provide data on land use, environmental impact, transport prospects and societal conditions. Areas of possible interest for further studies are identified. Altogether, SKB has carried out, or is in the process of carrying out, eight feasibility studies.

Site investigations are comprehensive investigations of the bedrock from the ground surface and in boreholes. In this phase, detailed studies are also made of how the facilities can be laid out and how transport can take place, as well as what the environmental consequences will be during construction and operation and following closure of the deep repository. Collected information is used to analyze and evaluate the site's suitability for a deep repository, particularly with regard to the properties of the rock.

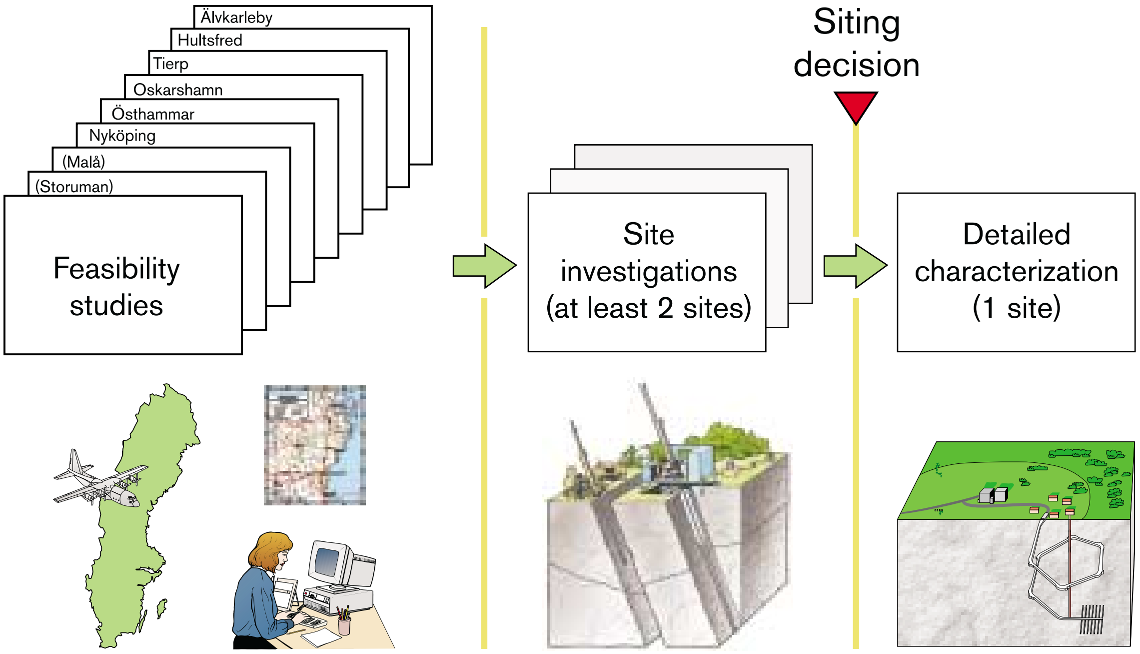


Figure 1-1. *Illustration of different phases on the way towards the deep repository.*

SKB is planning to investigate at least two sites in the country. Combining extensive field work on at least two sites with analysis work requires careful preparations, tight control and coordination of execution. In its decision /Ministry of the Environment, 2000/, the Government has stipulated conditions for SKB's comprehensive accounting prior to the site investigations. Among other things, it is stated that "The Government finds, like the Swedish Nuclear Power Inspectorate, that a distinct programme for site investigations should be prepared. Work on such a programme should be predicated on insights from the work on a safety assessment for the KBS-3 method...".

It is after concluded site investigations that the decision on siting of the deep repository will be made. After this siting decision, detailed characterization can be performed on one site. By means of investigations from tunnels, the properties of the bedrock can then be determined in detail and the construction of the deep repository planned.

Certain general premises influence the programme for the site investigations. One is quantities and types of fuel to be accommodated in the repository. This, together with data on burnup and interim storage time, is of direct importance for how big the repository will be and thereby what rock volume needs to be investigated. The site investigation programme is intended for investigating sites for a deep repository according to the KBS-3 method for spent nuclear fuel. Siting of the repository for other long-lived waste will not take place until about 30 years from now. A future co-siting with the deep repository cannot be ruled out. In that case, it a supplementary investigation programme will be required on an enlarged investigation area, but the investigation methods are expected to be roughly the same as presented in this report.

The KBS-3 method has been developed since the early 1980s /Pettersson et al, 2000/. It is a planning premise for the site investigation programme presented here. The main alternative of the KBS-3 method is that the canisters are deposited one by one in vertical holes from the deposition tunnels (Figure 1-2). Variants that may be considered are vertical deposition of two canisters in each hole, horizontal deposition of one canister per hole, and horizontal deposition of several canisters per hole. The present programme is also applicable to these variants.

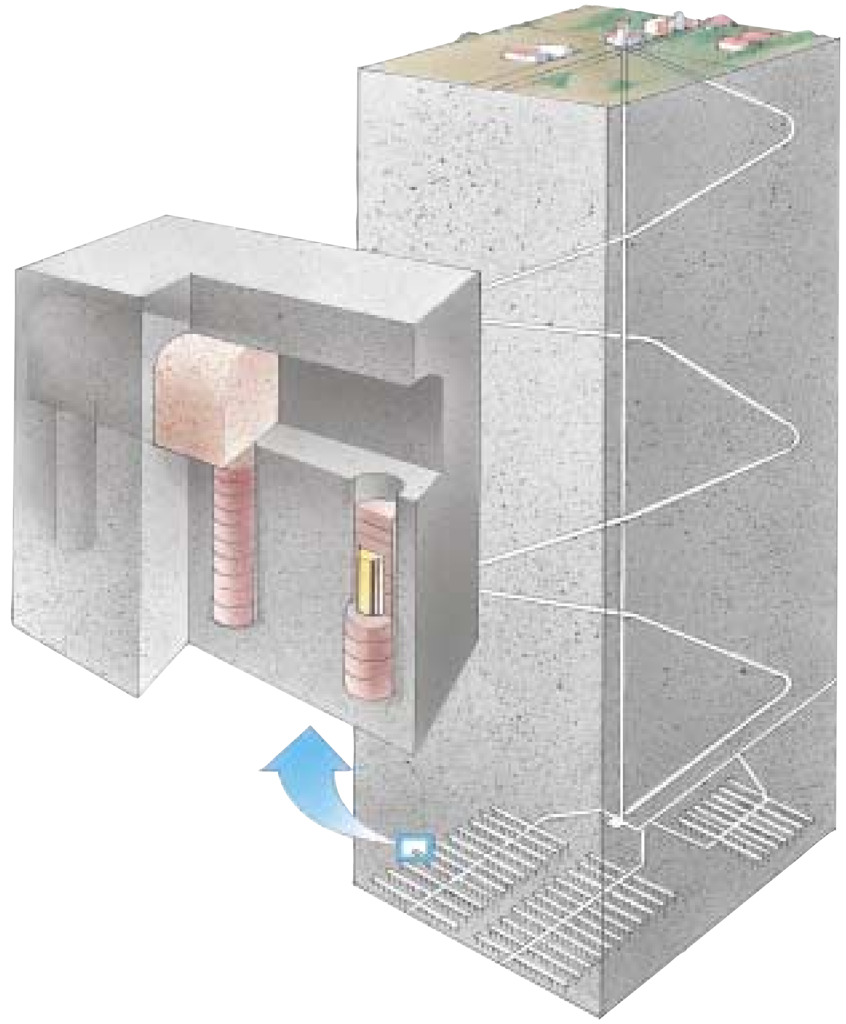


Figure 1-2. *The KBS-3 method with the main alternative that the canisters are deposited one by one in vertical holes. Variants with several canisters per hole or with horizontal holes may also be considered. The system is a planning premise for the site investigation programme.*

In SKI's evaluation /SKI, 1999/ of SKB's RD&D-programme 98, SKI concludes, among other things:

- "… that considerable work remains to be done to develop individual measurement methods and, particularly, to determine how different measurements should be combined into a suitable site investigation programme."
- "SKI therefore urges SKB to review, and if necessary, develop the measurement methods which can be used to determine parameters for the transport properties of the rock, already at the site investigation phase..."
- "In SKI's opinion, it is important that SKB, at an early stage of a site investigation, should prepare the necessary data for determining the large-scale flow pattern and regional trends in geochemical conditions…"
- "SKI also emphasizes that SKB, prior to the start of the site investigations, should present an overall programme for quality assurance of all of the components of a site investigation (measurement instructions and procedures, description and verification of measurement instruments, the management of data, including databases, evaluation methods, documentation etc)."

SKB believes that the comprehensive accounting that is planned prior to the site investigation phase answers these questions. The report on requirements and criteria /Andersson et al, 2000/ and the present report are the first two documents in this comprehensive accounting. Detailed investigation programmes with descriptions of investigation methods and measuring instruments plus the gradual site adaptation of the programmes complete the accounting, together with various procedures for e.g. data management, measurements and documentation.

1.3 Preparations for the site investigations

Generally speaking, Swedish crystalline basement offers good conditions for a deep repository, but it is nevertheless the local conditions that must be investigated in order to determine the suitability of a site. SKB already has long experience of site investigations. Between the end of the 1970s and the mid-1980s, a number of so-called study site investigations were carried out, above all in connection with the safety reports KBS-1, KBS-2 and KBS-3. It was during this period, when the purpose was to investigate different types of bedrock in different parts of the country, that the foundations of our knowledge of the Swedish bedrock, and how it is to be characterized with regard to factors of importance for a deep repository, were laid. Compilation reports have been published for the study sites where comprehensive investigations were carried out, e.g. /Ahlbom et al, 1991a/. For the most part, the investigations were conducted according to a standard procedure involving reconnaissance, investigations from the ground surface, investigations from boreholes and evaluation and modelling of the investigated site /Ahlbom et al, 1983/.

The Äspö Hard Rock Laboratory near Oskarshamn on the southeast coast of Sweden has also offered opportunities to try out and refine the methodology for site investigations. Based on the pre-investigations around Äspö, forecasts were made of geological, hydrogeochemical and rock-mechanical conditions, as well as of groundwater flows and the conditions for solute transport in the rock, before the underground laboratory was built. Then the forecasts were compared with observations and measurements in tunnels and boreholes under ground. Evaluations show that investigations on the ground surface, combined with analyses and modellings of various kinds, make it possible to reliably describe the properties and conditions in the rock that are important for a deep repository /Rhén et al, 1997a and b, Stanfors et al, 1997/.

A number of research projects have further contributed valuable experience regarding the properties of the bedrock via geoscientific investigations. This is particularly true of studies of the properties of fracture zones at the Finnsjön study site /Ahlbom et al, 1991b/, the Stripa Project /Fairhurst et al, 1993/ and the deep drillings at Laxemar. Relevant foreign experience has also proved valuable. Experience from Finland is particularly interesting, since the bedrock there resembles that in Sweden. In Finland, thorough site investigations have been conducted on four sites; in addition, borehole investigations have been conducted on additional sites.

Programmes for the site investigations are presented in several reports, which are being produced in steps. This report describes the general programme for investigation and evaluation of sites. Work is also under way on describing in detail the execution of the investigations in discipline-specific programmes. These programmes are also generic, i.e. not tailored to the specific conditions that will exist on a particular site. The level of detail in the discipline-specific programmes is great when it comes to e.g. which investigation methods will be used to determine the properties of the rock. Once the areas for site investigations have been selected, the discipline-specific programmes will be reworked into site-specific execution programmes. An overview of the various programmes is shown in Figure 1-3.

The need for geoscientific information is described in the parameters report /Andersson et al, 1996/. The need for information on surface ecosystems is described in /Lindborg and Kautsky, 2000/. The parameters report is based largely on experience from previous safety assessments of the KBS-3 method. The lists of geoscientific parameters are updated as new knowledge emerges. The parameters report and a report on requirements and criteria /Andersson et al, 2000/ and SR 97 /SKB, 1999a/ comprise important background documents for the programme writing work.

The parameters report presents and gives reasons for the parameters that are to be determined during a site investigation. The requirements and criteria report explains on what geoscientific grounds it is possible to determine the suitability of a site, while the programmes for the site investigations present a strategy for execution and how it is to be carried out. Finally, the investigation methods comprise the toolbox.

Besides programme writing, ongoing activities are development, testing and documentation of investigation methods and measuring instruments, plus production of an organization plan and quality procedures.

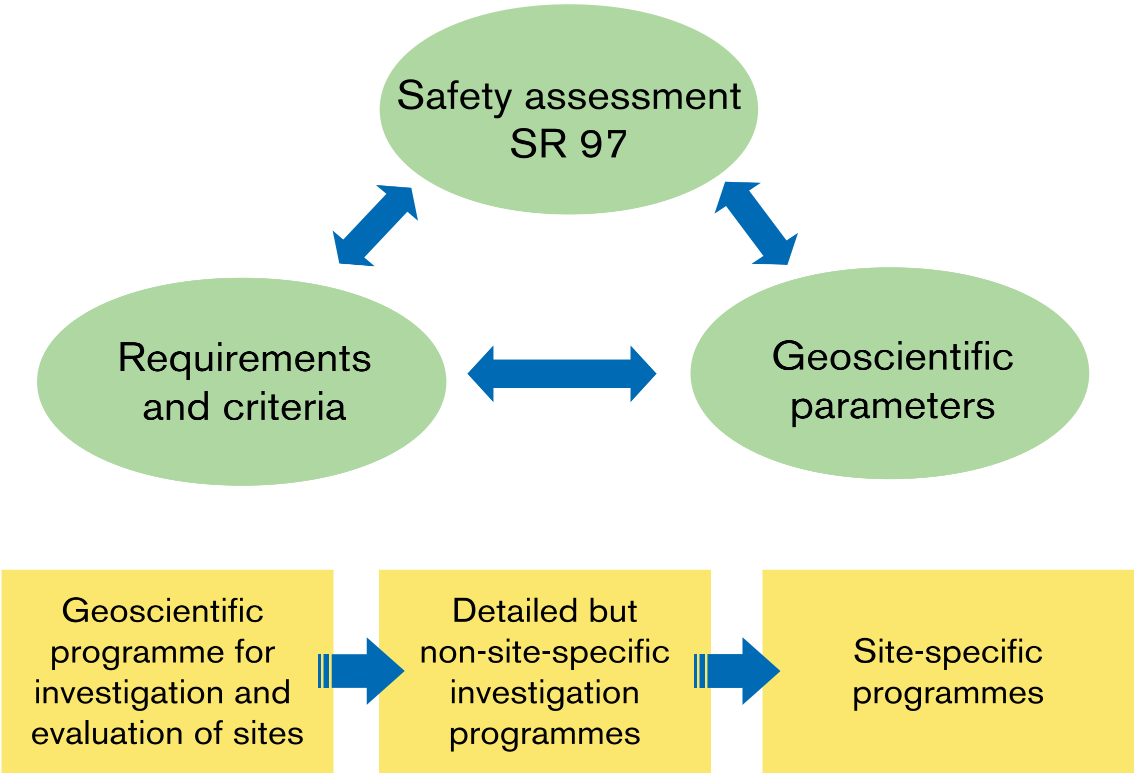


Figure 1-3. *Programme writing in steps leading up to the site investigations. Overview of important documents underlying the programme writing work. The investigation and evaluation programme is presented in this report.*

1.4 Terminology

In order to make the programme distinct, it is necessary to define certain central terms. Different siting phases were defined in section 1.2. This picture is augmented in the present section with terms used during the site investigation phase.

By *investigations* is meant all of the airborne, surface and downhole measurements, samplings and tests that are required on a site to obtain a comprehensive and sufficiently detailed picture of the site and its regional environs (site description). The site description is supposed to serve as a basis for designing the deep repository and for the safety assessment. This means that different investigation methods with associated measuring instruments are utilized in the field, that collected data are analyzed and interpreted, and that descriptive models are constructed (mainly geoscientific ones, but also for surface ecosystems).

By *design* is meant all the work of developing a facility description for a proposed siting, including layout above and below ground, plus definitions of constituent systems. Facility-specific technical and environmental risks in connection during construction and operation are identified. In this report, special emphasis is placed on layout proposals for underground chambers, including their access routes.

By *safety assessment* is meant the analysis that is required for site-specific evaluation of long-term safety with the proposed facility design. The safety assessment /SR 97, 1999/ includes the following:

- carefully describing the appearance of the repository system at some initial point in time, for example when it has been built and closed,
- surveying what changes the repository might undergo with time as a consequence of internal processes and external forces, and
- evaluating the consequences of the changes for long-term safety.

The investigations mainly provide material for the first point.

Design uses completed site descriptions to produce a site-specific facility description with layout. The safety assessment evaluates long-term radiological safety on the basis of site models and repository layout. The body of knowledge on the site evolves gradually, so that the various analyses of the site must also be done in stages. Results of previous analyses may also be used to narrow down the focus of the investigation activities in later stages. The different principal activities must therefore interact, Figure 1–4. The roles of the various actors are further elaborated on in this report.

A closely-related project has identified the requirements made by the deep repository on the rock /Andersson et al, 2000/. In addition, an account is given of 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 the site investigation phase. Chapters 4 and 5 show how this is to be applied during a site investigation.

The fundamental requirements that are made on the rock are also a point of departure in the ongoing preparation of detailed, discipline-specific programmes (Figure 1-3). In the work with requirements and criteria, pains were taken to define a number of terms. These terms have been included in Table 1-1 for the sake of completeness.

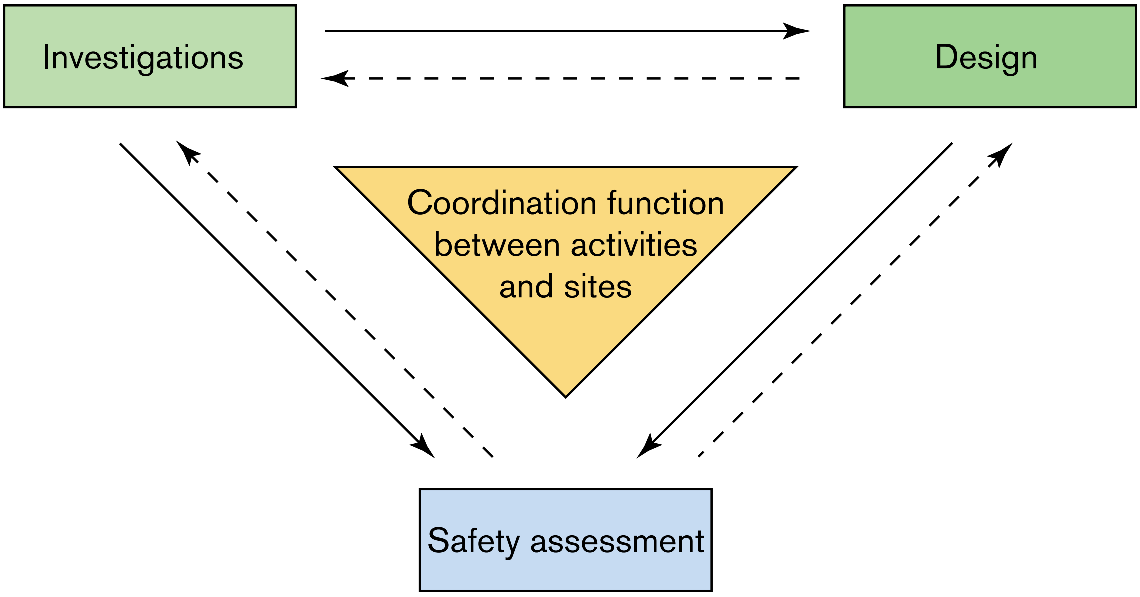


Figure 1-4. Illustration of the information flow between the three technical principal activities investigations, design and safety assessment, plus the important coordination function.

Table 1-1. Definitions of central terms for the site investigation phase.

Term	Definition
Candidate area	A geographic area proposed as suitable for further studies (site investigations) based on existing feasibility study material.
Site	A prioritized part of a candidate area that has been investigated in greater detail during a site investigation. Large enough to accommodate the deep repository and its immediate environs.
Site investigation	Comprehensive investigations of the bedrock from the air and the ground and in boreholes down to a depth of around one kilometre plus analyses and evaluation of the collected information.
Site evaluation	An overall evaluation of a site's suitability for a deep repository.
Investigations	Surface and downhole investigations that are required for a site to describe conditions on the site and its regional environs. (Investigation methods, measuring instruments, analysis, interpretation.)
Safety assessment	Assessment of long-term radiological safety.
Design	Collective term for the activity where all technical data are collected and processed to eventually be translated into a facility description, construction documents and design drawings.
Parameter	Physical or chemical quantity (property, condition or state in the rock).
Requirement (regarding rock)	Condition that must be satisfied. Refers to actual conditions regardless of siting phase. All requirements must be satisfied.
Preference (regarding rock)	Condition that ought to be satisfied regardless of siting phase. All preferences do not have to be satisfied.
Geoscientific suitability indicators	Measurable or estimable site-specific parameters that can be used in a given siting phase to assess whether requirements and preferences are satisfied.
Criteria for site evaluation	Values for suitability indicators in a given siting phase that can be used to assess whether a site satisfies stipulated requirements and preferences.

1.5 This report

With the Government’s decision on RD&D-Programme 98, statements of comment from the Swedish Nuclear Power Inspectorate and viewpoints from the feasibility study municipalities as a point of departure, SKB intends to submit a supplementary account. This is planned to be done in a report, RD&D 98 – Supplement, with the sections “Choice of method”, “Choice of site” and “Programme for site investigations”. Figure 1–5 provides an overview of the scope of RD&D 98 – Supplement, and shows all main references.

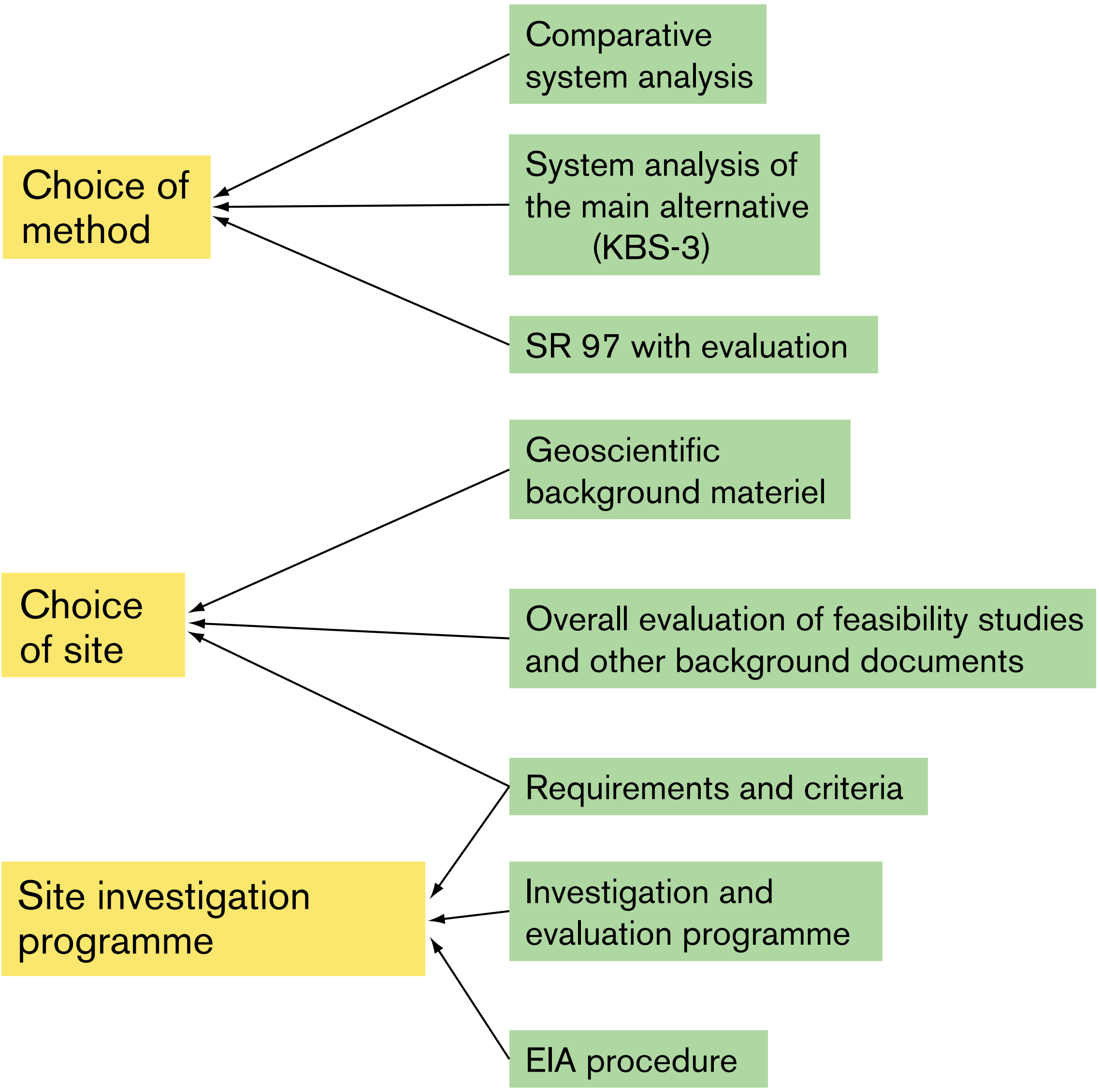


***Figure 1-5.** Overview of SKB’s comprehensive accounting prior to the site investigation phase, i.e. the supplement to RD&D 98. Investigation and evaluation programme (this report) is one of the main references.*

The present report comprises a basis for the RD&D 98 – Supplement's part on programme for site investigations.

Chapter 2 gives an account of the environmental consequences of the investigations plus legal requirements, environmental considerations, and communication with concerned parties.

Chapter 3 discusses the strategy for the planning of the investigations and the evaluation. Goals for the site investigation phase, as well as the purposes of the different principal activities, are also presented. The most important products are presented and discussed.

Chapter 4 gives an account of the execution of the investigations to gather necessary site-specific information. Available investigation methods are listed in an appendix to the report.

Chapter 5 describes how the gathered site-specific information is evaluated from various aspects and how this is coordinated.

Chapter 6 discusses quality aspects during a site investigation and presents vital tools for database management and modelling.

Chapter 7 deals with organization and necessary resources for the execution of the site investigations on a general plane. Time required is also taken into account.

2 Environmental considerations and laws

This chapter provides a brief description of the planned field activities. The purpose is to provide a picture of how the investigations will be noticed on the site, what impact the field work may have on the environment and how SKB intends to minimize any adverse environmental effects. The description does not delve into how or why the investigations will be conducted, or what the results will be. Such information is presented in Chapters 3–5.

The chapter further provides an overview of what laws and ordinances are applicable during a site investigation and what permits may be required. In order for investigations to be conducted, the landowner must give his permission for drilling and investigations as well as for the necessary road construction. Besides the fact that laws must naturally be complied with, SKB considers it important that the activities be conducted in consensus with those affected by them.

2.1 Description of environmental impact

2.1.1 Background

The purpose of the site investigations is to acquire greater knowledge regarding above all the in-depth properties of the rock. To accomplish this, data must be collected. The need for data is the primary factor that will guide field activities during the site investigations. What is possible and suitable to do is, however, also determined to a great extent by environmental conditions on the site. Relatively extensive measurements will be made from the air, from the ground and in boreholes. To enable the measurements to be performed quickly and conveniently, some small roads may have to be built and power lines run up to the drilling sites.

A site investigation cannot be compared directly to an ordinary construction or civil engineering project. Even though the investigated surface area is large (5–10 km^2), field activities are mainly concentrated to individual measurement sites within the area. Investigations will also be conducted in a larger surrounding area, but only to a limited extent.

The activities will be adapted to the natural and cultural values of the site so that the impact is limited. The description provided in this report cannot be very detailed, since it is not based on a real site. Exactly how the activities will be adapted to conditions on a real site will therefore be discussed in the site-specific programmes that will be presented on a later occasion. For this work, SKB will consult with the concerned municipalities and landowners. Similarly, organizations and private persons with specialized local expertise concerning e.g. the study site's natural and cultural values will be consulted.

Protected areas will be avoided wherever possible. The same applies to other areas that may be sensitive to disturbances, such as breeding areas for unusual bird species and localities with rare plants. As far as breeding areas are concerned, it is often particularly important to avoid disturbing breeding birds during a certain time of the year.

With good knowledge concerning the study site's flora and fauna, the field activities can be adapted so that any disturbances will be limited. This can be achieved without compromising the quality of the investigation results, although the investigations may in some cases take longer for this reason.

2.1.2 Measurements from the air

Airborne geophysical surveys will probably be conducted at the beginning of the site investigations. A helicopter or an aeroplane will then be equipped with instruments so that several different measurements can be performed simultaneously. The measurements are conducted along flight lines spaced at intervals of 50–100 m.

In airborne surveys, the measurement instruments are built-in and permanently mounted on the plane, while in helicopter surveys they are suspended below the helicopter. The measurements are performed from an altitude of 30–60 m. The noise this makes can be disturbing while the survey is in progress, usually a period of several days. Airborne surveys do not require any ground support activities besides a landing strip, which is likely to be located outside the area.

2.1.3 Measurements from the ground

Surveys performed from the ground surface are gathered under this heading.
The following methods are most likely to be used:

- inventory and documentation of the area's ecosystem,
- geological mapping,
- ground geophysical surveys,
- hydrological surveys,
- hydrogeochemical studies.

Documentation of the original conditions in the area's ecosystems as well as follow-up of how they are affected by the site investigations will be carried out. With this knowledge, it will also be possible to adapt the investigation activities so that valuable natural and cultural values can be protected and conserved so that biological diversity is preserved. For the site where the deep repository will be built, this documentation provides baseline values for the follow-up of the evolution of the ecosystems.

Geological mapping involves one or more geologists walking around the area and making systematic observations of the bedrock and soil strata. Simple sampling of rock and soil is also performed. The working tools used are hammer and spade. Geological mapping of the bedrock sometimes requires exposing the rock surface along certain profiles. The extent of this invasive work will be dependent on the thickness of the soil cover and how much natural exposure there is of the rock in the area. Sometimes power excavators must be used. If the soil layer is thick and there are few rock outcroppings, sounding and drilling through the soil layers may instead by resorted to in order to ascertain the depth of the rock surface and to obtain rock samples. Light hand-held or small crawler-mounted drills are used for this.

Various kinds of measuring instruments are used for geophysical ground surveys. Certain measurements are easily performed with light hand-held instruments, while others require more extensive work and bigger equipment. For some methods, cables are laid along lines or in loops. All such arrays are temporary and cause no damage to the ground or other environmental impact. In some cases, stakes are set out to mark measuring points or profiles.

In one type of geophysical measurement, small explosive charges are placed in boreholes in a limited area or along profiles. They cause minor pits or humps.

All in all, it can be said that geophysical surveys, like geodetic surveys (measurement of position and elevation coordinates) seldom cause permanent scars in the landscape. If the vegetation is dense and tangled, some clearing has to be done to provide adequate visibility and accessibility along the survey lines. Depending on the nature of the ground, this may leave some ruts, but in comparison with e.g. ordinary logging activities, this ground impact is insignificant.

The hydrological and hydrogeochemical surveys include mapping natural watercourses and taking water samples, which normally does not require any invasive work at all. Mapping of catchment areas and measurement of water discharge rates may, however, require placing measuring stations in rivers and streams. A small measuring weir or other device can then be built to gather the water flow into a measurable stream. Measuring tubes will be positioned at suitable places for measurement of the level of the water table. Similarly, some meteorological measuring stations will be put out. None of this can normally be regarded as disturbing.

2.1.4 Drilling

Drilling is the “heaviest” activity during the site investigations. It also causes the greatest environmental impact. Two main types of holes are drilled: cored boreholes and percussion boreholes. They entail different types of intervention on the site. The deeper cored boreholes are drilled with bigger machines.

An area of at least 100 m^2 is levelled and covered with gravel at each drilling site, see Figure 2-1. A drilling rig for core drilling is powered by a diesel engine that generates noise and exhaust emissions of the same magnitude as a small truck engine. The actual drilling rig consists of a rotation unit that holds and drives the drill string with drill bit. There is also a mast or a tower for handling up to 12-metre-long pipes. Strict requirements are made on the careful handling of all fuels and lubricants on the drilling site. Leaks that can penetrate down into the ground or the borehole are not accepted, both for environmental reasons and because such spills can jeopardize later water sampling. Any unintentional leaks are collected on the site by means of cover cloths placed on the ground around the borehole. Equipment for immediate cleanup of oil spills is also on hand as an extra precaution.

A work crew on a drilling site normally consists of three to four persons, including a site geologist. The site geologist is the work supervisor and inspects and maps the drill cores that are taken up out of the borehole during drilling. A number of freight containers and sheds are placed near the drilling rig for use as storeroom, workshop, site geologist’s office and personnel quarters.

Figure 2-1. *Core drilling on a prepared drilling site served by a road.*

A 1,000-metre deep cored borehole takes around two to three months to drill. During drilling, clean water (flushing water or drilling water) is pumped to the drilling site from a rock-drilled water supply well near the cored borehole or is fetched by tank truck. On the drilling site, the flushing water is stored in tanks next to the drilling rig before being pumped down into the borehole.

Most of the flushing water is pumped back up out of the borehole, after which it is conducted away. Pumping out of the borehole is performed as airlift pumping, which means that the drilling water is forced up out of the borehole by compressed air. A diesel generator is used to generate the compressed air, and like the drilling rig's engine the generator gives rise to noise and exhaust emissions roughly equivalent to those from a truck engine.

As long as airlift pumping is in progress, the water level in the borehole is depressed about 40–60 m below the normal groundwater level. The amount of this "drawdown" decreases with the distance from the borehole. At a distance of 200–400 m the drawdown is not noticeable. A drawdown of 40–60 m applies only to the bedrock immediately surrounding the borehole. The impact in overlying soil strata is completely dependent on the composition of the soil strata and the nature of the soil-rock interface. With dense soil strata and poor hydraulic contact between soil and rock, the drawdown in the soil strata is reduced or eliminated entirely. When airlift pumping ceases, the groundwater level in the rock resumes its original level within a day or two.

Drilling grinds down the rock to fine-grained material called cuttings. A great deal of this material is mixed up with the drilling water and accompanies the return water that is pumped up out of the borehole. The return water is therefore not discharged directly into a watercourse, but first passes through basins so that most of the drill cuttings can settle out. It is also analyzed for chemical composition. If the groundwater pumped up to the surface has a high salinity, for example, measures may be taken to prevent damage to the flora and fauna. Such measures may include diluting the water, conducting it to larger watercourses or hauling it away in tanks.

The second type of borehole used is percussion boreholes. Percussion drilling is performed with ordinary well drilling rigs, which are generally crawler-mounted. When water-bearing fractures are reached, the return flow consists of a mixture of air, mud and water, which is collected and conducted to a settling basin. During percussion drilling as well, the groundwater level is depressed around the borehole. The size of the drawdown and the time required for recovery are comparable to those described for core drilling.

When drilling is finished, the borehole is secured for further use, regardless of whether it is a cored borehole or a percussion borehole. The borehole is capped with a cast-on steel casing pipe that sticks up a few decimetres above the surface of the ground. At cored boreholes, a cement slab several square metres in size is poured around the casing pipe. The casing pipe is locked, and often a small measurement container is placed over the borehole (see Figure 2-2).

The boreholes will be distributed all over the investigation area. The location of each individual borehole is determined by data requirements, which vary for different boreholes. Usually the holes are drilled at an angle in order to penetrate a fracture zone at a certain depth, for example. When the boreholes are set out, such factors as ordinary land use and the natural and cultural values of the site will be taken into consideration. The position of the borehole can be adjusted by varying its drilling angle.

In summary, it can be concluded that core drilling is the “heaviest” activity with the greatest environmental impact in a site investigation. Core drilling can, however, be limited to no more than 20 or so drilling sites with a duration of a few months per site. Three to four drilling rigs will probably be in operation simultaneously within the investigation area. The noise from a drilling rig is roughly comparable to the noise from a logging machine. But a logging machine moves over larger areas than the drilling rigs, which are stationary during the drilling of each hole.

Figure 2-2. *Drilling site with measurement container placed over a finished borehole, in this case with equipment for long-term monitoring of groundwater levels.*

2.1.5 Measurements in boreholes

After completion, the boreholes are used for various kinds of measurements, conducted in campaigns. Each measuring period can range from a few days to a couple of months per borehole, with a total maximum measuring period for the area of around one year. After that, permanent drilling equipment is usually installed for long-term recording of e.g. groundwater levels.

For measurement in the boreholes, long wire ropes or pipe strings are needed to handle the measuring instruments and electric cables for signal transmission. This equipment can seldom be handled manually, but requires a winch or other lifting tackle. The equipment is transported on a car trailer or by truck to and from the borehole.

Hydraulic tests and water sampling requires more elaborate lifting and measuring equipment than most other methods. Hydraulic testing equipment is often mounted in freight containers or mobile carts that are positioned directly above the borehole. In connection with water injection tests and pumping tests, water is handled in a way that resembles flushing and return water handling in connection with drilling. But the water quantities are much smaller than in connection with drilling, and return water contaminated with drill cuttings does not have to be disposed of. In connection with long-term pumping tests, however, the water quantities can be relatively great, and if the pumped-up water has high salinity, it will be disposed of in the same manner as that recovered from drilling. All measurements at the borehole cause less environmental impact than drilling, above all they are less noisy. On the other hand, the measurements are often conducted over a relatively long period of time.

2.1.6 Logging roads and electricity supply

Personnel and equipment for drilling and measurement can be transported on roads similar in quality to ordinary logging roads. Without roads, personnel and equipment have to be transported over the terrain, giving rise to rutting which can be extensive and more damaging than roads.

The investigations will probably require around ten kilometres of logging roads. How much road construction will be necessary depends on the existing road network. The roads built to drilling sites should be at least three metres wide and be able to bear at least 25 tonnes. The roads will be adapted to the conditions on the site wherever possible.

The activities at the drilling site require electricity. If a mains supply is not available, electricity must be supplied by diesel-powered generators. The generator alternative emits exhaust gases and noise roughly equivalent to those emitted by a small truck engine and is furthermore less reliable than electricity from a public grid. On the other hand, a mains supply often requires installation of electric cables in the initial stage of the site investigations.

2.1.7 Transportation

Both material and personnel will be transported on the roads throughout the site investigation phase. Most of the transportation consists of passenger transport of drilling and measuring personnel. Heavy transport takes place mainly during drilling and the first measurement period.

2.1.8 Visitors

The consultation and public relations activities which SKB will conduct during the site investigation phase will lead to a large number of visits to the investigated sites. The visits will be organized so that areas with plants or animal life that could be damaged or disturbed by humans are avoided. The occurrence of unique habitats or particularly sensitive breeding areas may require periodic interruptions or other restrictions in both measuring and visiting activities.

2.1.9 Site office

A site office will probably be established in the community. A simple office may also be needed on the actual investigation site. Depending on the distance to the site office, this field office may have different roles. In any event, the field office will have personnel and working quarters as well as storage and workshop facilities. Even if the site investigations go on for several years, the field office will be housed in building barracks or the like. As mentioned previously, various freight containers will be placed temporarily or for longer periods at the boreholes, and possibly at the field office as well.

2.2 Applicable laws and required permits

The most laws that specifically regulate the final disposal of nuclear fuel are the Nuclear Activities Act (SFS 1984:3) and the Environmental Code (SFS 1998:808). No nuclear activity will be conducted during the site investigations, however, so the Nuclear Activities Act will not be applicable during this phase. The site investigations will include construction and civil engineering activities on a comparable scale to the subsequent detailed characterization and deep repository construction phases. Nevertheless, the investigation activities must of course comply with the general rules of consideration and provisions laid down in the Environmental Code. Examples of other laws that may be applicable to a site investigation are the Planning and Building Act and the Cultural Monuments Act.

After site investigations, before SKB can proceed with detailed characterization of the candidate repository site, permits for siting of the deep repository must be applied for and granted under the Environmental Code and the Nuclear Activities Act.

2.2.1 Environmental Code

The Environmental Code is "*aimed at promoting sustainable development whereby present and future generations will be guaranteed a healthy and good environment.*" The intention is that "*the Environmental Code will be applied so that*

1. *human health and the environment are protected against damage and nuisance, irrespective of whether these are caused by pollution or other influence,*
2. *valuable natural and cultural environments are protected and conserved,*
3. *biological diversity is preserved,*
4. *land, water and the rest of the physical environment are used so that, from an ecological, social, cultural and socio-economic viewpoint, the long-term good management of resources is ensured, and*
5. *reuse and recycling, as well as other conservation of materials, raw materials and energy, are promoted so that closed-loop recycling is achieved.*"

How these environmental frames will be applied is manifested in the programmes and plans that govern the execution of the site investigations.

The following concepts are defined in the Environmental Code:

- Environmentally hazardous activities.
- Water undertakings.
- Protected areas.

Possible environmental impact during the site investigations is regulated under these concepts. Whether any part of the activity requires a permit or exemption is also shown here.

By *environmentally hazardous activities*, which are dealt with in Chapter 9 of the Environmental Code, is meant emissions to land and water and activities that entail other nuisance to human health and the environment. These include polluting emissions of gas, water and other substances as well as disturbing noise, vibration, light, etc. Road construction and drilling are examples of site investigation activities that could entail certain nuisances, mainly as regards noise. According to the main rule in "Ordinance concerning environmentally hazardous activities and public health" (SFS 1998:899), a site investigation is not one of the activities for which a permit or notification are required.

By *water undertakings*, which are dealt with in Chapter 11 of the Environmental Code, is meant mainly measures in water areas aimed at changing the depth or location of the water, affecting the groundwater by diversion or supply of water or construction of installations, and land drainage. Examples of measures during a site investigation that could involve water undertakings are road construction in water areas and extensive pumping from boreholes. Water undertakings require a permit, unless it is clearly apparent that neither public nor private interests are harmed.

By *protected areas*, which are dealt with in Chapters 7 and 8 of the Environmental Code, is meant areas that are protected for the purpose of preserving valuable natural and cultural environments and to preserve biological diversity. Such areas may, for example, be areas subject to shore protection, water protection, and nature or cultural reserves. If site investigation is planned within such an area, the relevant protection provisions must be observed, and an exemption may be required to carry out the investigation.

Activities or measures that belong to the above categories are thus regulated by the Environmental Code, and sometimes a permit or exemption is required to conduct such an activity. Site investigations are no generally judged to entail extensive environmental impact, and no general permit is required. However, not until areas for site investigations have been selected will it be possible to determine whether any specific activity during the site investigations may require a permit.

2.2.2 EIS and consultations for the deep repository and site investigations

SKB has already during the feasibility studies initiated a consultation procedure with concerned municipalities, county administrative boards and national authorities. When site investigations commence, SKB intends to formally notify the deep repository matter to the county administrative board for consultation in compliance with the provisions of the Environmental Code. The extended consultations will subsequently proceed during the entire site investigation phase. SKB's goal is that this should result in a carefully conceived and broadly supported environmental impact statement (EIS) for the selected site as a basis for a decision in the deep repository matter.

After candidate areas for site investigations have been presented, SKB will notify the matter to the municipalities in question in plenty of time and try to reach agreement with landowners. SKB also prepares site-specific programmes for the investigations, in which the environmental consequences of the investigations are also dealt with. For the purposes of this programme writing process, questions such as environmental consideration and adaptation to the natural conditions on the site are discussed within the framework of the consultations, already initiated at this point. It may then become apparent, as noted above, whether any specific activity during the site investigations may require a special permit.

The site investigations are not expected to lead to significant environmental impact, but the matter of site investigations will nevertheless be notified to the county administrative board in accordance with Chapter 12 of the Environmental Code. This gives the county administrative board an opportunity to offer advice on the site investigations and to determine whether a permit may be required for any specific activity during the site investigation.

Regardless of how a permit procedure for a specific activity during the site investigations is initiated, it will be handled as a special case which also requires a special investigation of the environmental consequences of this activity. The consultation procedure for this special case should, however, be able to take place within the framework of the regular consultations.

2.2.3 Other laws

The Planning and Building Act and the Cultural Monuments Act were mentioned previously as possibly being applicable to certain activities during the site investigations.

The Planning and Building Act regulates the erection of buildings. Normally, requirements are made on permits for construction, unless the municipality has decided in the detailed development plan or area regulations that a building permit is not needed. A ground permit for earthmoving, filling, etc is normally only required within areas subject to detailed development plans, but a municipality may decide that a ground permit is also included in area regulations. Road construction is regulated by the Road Act. But it only applies to public roads, so it will probably not be applicable to the simple logging roads that will be built during the site investigations. However, construction of these roads may require consultation (under Chapter 12 Section 6 of the Environmental Code) with the county administrative board.

The Cultural Monuments Act entails an obligation for SKB to find out in plenty of time whether any stationary ancient monument will be affected by the site investigations. If a special investigation is required to find this out, it shall be paid for by SKB. If it is established that a stationary ancient monument will be affected, consultation shall take place immediately with the county administrative board. By stationary ancient monument is meant graves, rock carvings, remains of settlements, political assembly sites, ruins and the like.

If a stationary ancient monument is encountered during excavation or other work, the part of the work that affects the ancient monument shall immediately be interrupted. The person in charge of the work must immediately notify the conditions to the county administrative board. A permit from the county administrative board is required to alter, displace or remove a stationary ancient monument. Such a permit can only be issued if the ancient monument gives rise to an obstacle or nuisance that is not in reasonable proportion to the importance of the ancient monument. The county administrative board may combine the permit with conditions stipulating that the find shall be examined and/or taken care of in some special way, measures which shall normally be paid for by the person conducting the activities.

2.3 Access to the study site

Having access to the land is naturally a prerequisite to carrying out the site investigations. Private ownership is heavily protected by law in Sweden. The right of public access stands in opposition to private ownership, but is not particularly clearly defined. Certain limited inspections in the field could probably be carried out under the right of public access, but carrying out actual investigations involving, for example, drilling requires the landowner's permission. It is in SKB's interest not only to obtain the landowner's permission, but also to consult with him regarding the execution of the activities. Reasonable compensation will be paid for restrictions in the landowner's freedom to utilize his land and for any damage caused.

3 Goals, stages and results

This chapter presents SKB's overall goals during the site investigation phase and the purposes of the two stages of the site investigation phase: initial and complete site investigation. It also presents the expected results of the principal activities *investigations*, *design* and *safety assessment*.

3.1 Goal of the site investigation phase

The goal of the site investigation phase is to obtain the permits that are required to site and build the deep repository. The geoscientific work during the site investigation phase is supposed to provide the broad knowledge base that is required to evaluate the suitability of investigated sites for a deep repository. The material must be comprehensive enough to:

- show whether the selected site satisfies fundamental safety requirements and whether civil engineering prerequisites are met,
- permit comparisons with other investigated sites, and
- serve as a basis for adaptation of the deep repository to the properties and characteristics of the site with an acceptable impact on society and the environment.

The work is being carried out in consultation with municipalities, regulatory authorities and nearby residents.

When investigations and other studies have been completed and the results analyzed, SKB will decide whether the necessary conditions have been fulfilled for submitting an application for a permit for siting of the deep repository on one of the sites. If so, the application will be submitted along with the environmental impact statements that have been prepared in consultation with all concerned parties. Permit and permissibility review will then take place under the Nuclear Activities Act, the Environmental Code and the Planning and Building Act. If a permit is obtained, the detailed characterization phase will commence.

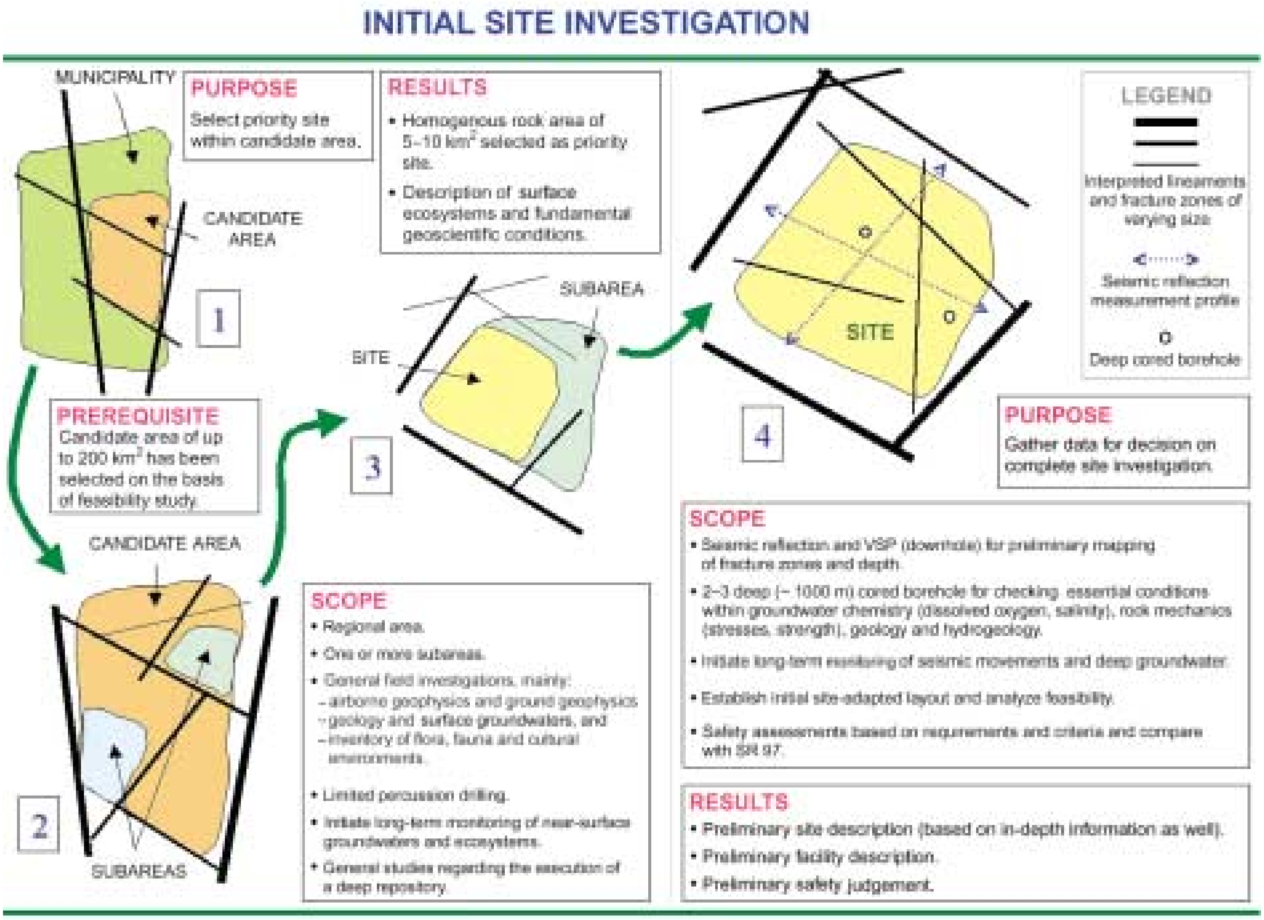
3.2 Stages

The site investigation phase is so great in scope in terms of time, space and content that it must be subdivided into stages to permit a rational execution of all investigations and analyses. Dividing the work into stages also better enables the investigation methods to be adapted to conditions on the site and permits more effective feedback from the evaluation.

To achieve the main goals of the site investigation phase, at least two sites within the candidate areas from the feasibility studies will be investigated. The size of the candidate areas is dependent on how precisely a possible siting of the deep repository has been able to be fixed based on existing feasibility study material, but it can be up to a couple of hundred square kilometres. In other words, the preconditions in the selected candidate areas are not equal as regards the size of the area of interest and knowledge of the geological conditions. The first task will therefore be to bring the areas up to a comparable knowledge level, define the site that will be investigated in greater depth, and acquire knowledge on the rock conditions at repository depth. This stage is called *initial site investigation*, see Figure 3-1. By "site" is meant the area required to accommodate a deep repository with good margin and its immediate environs, roughly 5–10 square kilometres.

The main purpose of the initial stage is:

- to identify and select the site within a specified candidate area that is deemed to be most suitable for a deep repository and thereby also the part to which further investigations will be concentrated, and
- to determine, with limited efforts, whether the feasibility study's judgement of the suitability of the candidate area holds up in the light of in-depth data.



PURPOSE
Select priority site within candidate area.

RESULTS
- Homogenous rock area of 5–10 km^2 selected as priority site.
- Description of surface ecosystems and fundamental geoscientific conditions.

PREREQUISITE
Candidate area of up to 200 km^2 has been selected on the basis of feasibility study.

SCOPE
- Regional area.
- One or more subareas.
- General field investigations, mainly:
  - airborne geophysics and ground geophysics
  - geology and surface groundwaters, and
  - inventory of flora, fauna and cultural environments.
- Limited percussion drilling.
- Initiate long-term monitoring of near-surface groundwaters and ecosystems.
- General studies regarding the execution of a deep repository.

Interpreted lineaments and fracture zones of varying size

Seismic reflection measurement profile

Deep cored borehole

PURPOSE
Gather data for decision on complete site investigation.

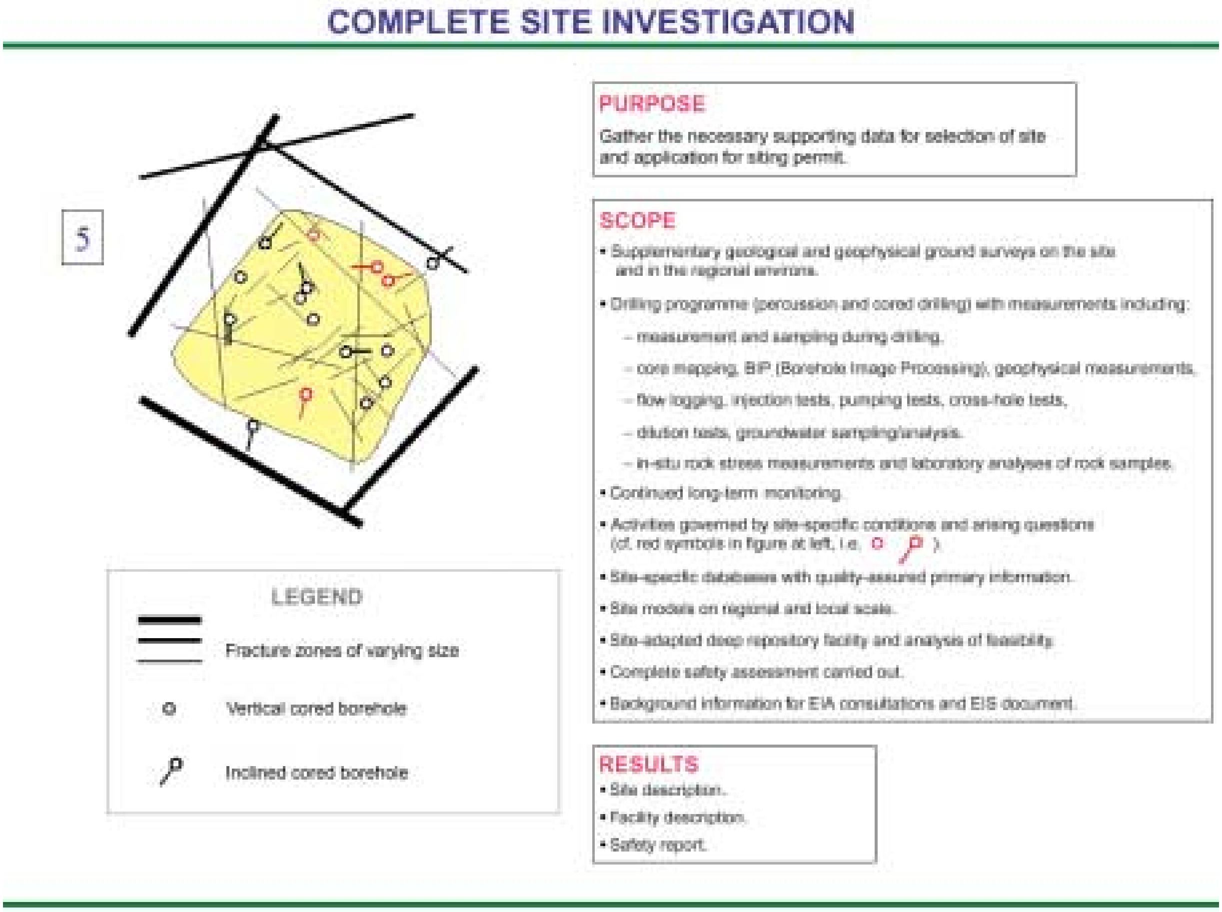
SCOPE
- Seismic reflection and VSP (downhole) for preliminary mapping of fracture zones and depth.
- 2–3 deep (~ 1000 m) cored borehole for checking essential conditions within groundwater chemistry (dissolved oxygen, salinity), rock mechanics (stresses, strength), geology and hydrogeology.
- Initiate long-term monitoring of seismic movements and deep groundwater.
- Establish initial site-adapted layout and analyze feasibility.
- Safety assessments based on requirements and criteria and compare with SR 97.

RESULTS
- Preliminary site description (based on in-depth information as well).
- Preliminary facility description.
- Preliminary safety judgement.

Figure 3-1. *Conceivable scope of, and activities during, an initial site investigation.*

If the overall assessment shows that the prospects for siting a deep repository on the investigated sites are still good, *complete site investigations* follow on these sites, see Figure 3-2. The purpose of the complete site investigations is to gather the material that is required to select a site and apply for a permit for siting of the deep repository. This means that knowledge of the rock and its properties needs to be increased so that:

- a geoscientific understanding of the site can be obtained as regards current states and naturally ongoing processes,
- a site-adapted repository layout can be arrived at,
- an analysis of the feasibility and consequences of the construction project can be done, and
- a safety assessment can be carried out to determine whether long-term safety can be ensured on the site.



PURPOSE

Gather the necessary supporting data for selection of site and application for siting permit.

SCOPE

- Supplementary geological and geophysical ground surveys on the site and in the regional environs.
- Drilling programme (percussion and cored drilling) with measurements including:
  - measurement and sampling during drilling,
  - core mapping, BIP (Borehole Image Processing), geophysical measurements,
  - flow logging, injection tests, pumping tests, cross-hole tests,
  - dilution tests, groundwater sampling/analysis,
  - in-situ rock stress measurements and laboratory analyses of rock samples.
- Continued long-term monitoring.
- Activities governed by site-specific conditions and arising questions (cf. red symbols in figure at left, i.e. ○ ⚲).
- Site-specific databases with quality-assured primary information.
- Site models on regional and local scale.
- Site-adapted deep repository facility and analysis of feasibility.
- Complete safety assessment carried out.
- Background information for EIA consultations and EIS document.

RESULTS

- Site description.
- Facility description.
- Safety report.

Figure 3-2. *Conceivable scope of, and activities during, a complete site investigation.*

3.3 Expected results

The work during the site investigation phase is planned so that a body of knowledge is progressively built up that can serve as a basis for comparison between the sites. The emphasis in the work will naturally lie on investigations of the rock, since it is there the lack of knowledge is greatest today. As knowledge of the rock is acquired, the surface and underground parts of the facility can be designed, safety assessments can be carried out based on site-specific data, and the facility's impact on society and the environment can be assessed.

The activities planned by SKB during the site investigation phase are shown in Figure 3-3. The expected results of the principal technical activities *investigations*, *design* and *safety assessment* can be specified in the form of different products for each investigated site.

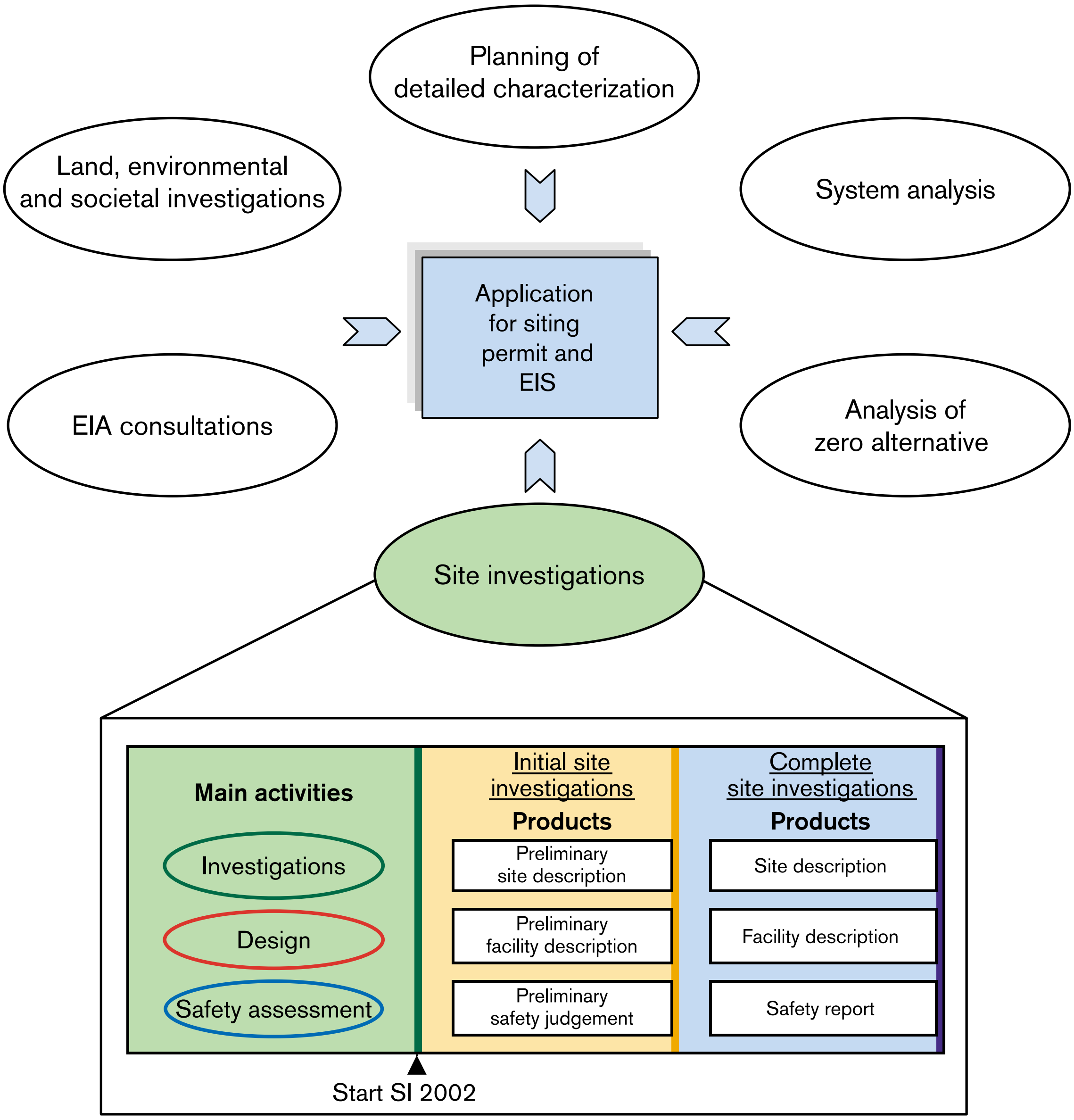


Figure 3-3. *Illustration of the activities and products which SKB expects during the site investigation phase. The products are a part of the supporting documentation to be submitted together with the application for a siting permit for the deep repository. Activities are shown in the figure as ovals, while products are shown as rectangles.*

3.3.1 Main products after completed site investigation

The main product of the investigations is a *site description*, which presents collected data and interpreted parameters that are of importance both for the overall scientific understanding of the site and for the analyses and assessments that are made of design and safety assessment with respect to the deep repository's layout and construction as well as its long-term performance and radiological safety. The information is collected in a database. The site description should furthermore present an integrated description of the site (geosphere and biosphere) and its regional environs with respect to current state and naturally ongoing processes. Geoscientific models and models for surface ecosystems are devised for this purpose.

The main product of design is a *facility description*, which presents layout proposals with associated construction analyses based on data reported from investigations. Site-specific design criteria that define the conditions for the various rock works that have to be done are also presented, such as requirements on rock reinforcement, rock sealing or choice of material for backfilling. A technical risk evaluation is carried out, by which is meant a description of uncertainties in calculations and the environmental impact of the civil engineering work. The facility description includes the choice of technology and repository layout, plus an establishment description.

The main product of the safety assessment is a *safety report*, which analyzes whether long-term safety is ensured for the planned deep repository based on reported investigation results and the proposed repository layout. The safety assessment includes analyses of technical, hydraulic, mechanical and chemical processes around a deep repository as well as calculations of radionuclide transport. Data after completed site investigation should serve as a basis for an assessment of at least the same scope as the SR 97 safety assessment /SKB, 1999a/. The methodology in SR 97 hereby comprises a basis for the methodology to be used in future safety assessments.

As far as other siting documentation is concerned, such as *land*, *environmental and societal surveys*, in-depth and detailed studies are carried out to obtain a sufficient body of material for a siting application in this respect as well.

In addition to the site-specific documentation underlying the choice of site, a body of material is needed to describe the deep repository system and the continued activities on the selected site. This work will preliminarily comprise the following reports:

- An updated *system analysis* with a description of the design of the entire system for final disposal of the spent nuclear fuel, plus the variants in the design of the KBS-3 system that are still of interest for further study. The results of the technology development that has taken place during the site investigation phase are also presented here, the choice of technology is explained, and a comparison is made of how different choices influence long- and short-term safety as well as of how different parts of the system influence each other.
- A *programme for the detailed characterization phase* with a description of how the tunnel down to repository depth will be constructed and how the rock will be investigated in detail from these tunnels. Construction of buildings, roads and railways on the surface will also be described. The environmental impact of the construction activities and the measures that will be take to limit this impact will be described along with a control programme. A plan will also be presented for how consultations with concerned parties will take place during the detailed characterization phase.

- An account of the *zero alternative*, i.e. what happens if the deep repository is not built and instead supervised storage of the spent fuel in CLAB continues for an indefinite time (possibly several hundred years).

All the material described above will be gathered and discussed throughout the site investigation phase, not least in the environmental impact assessment (EIA) consultations. The *Environmental Impact Statement* (EIS), which is the result of an EIA process, can be seen as a document intended to provide a comprehensive picture of the environmental consequences of the deep repository. A proposal for the contents of the EIS is found in an appendix to RD&D 98, section 5.4 /SKB, 1998/. It is through the EIA consultations and in the final EIS that an integrated account will be given of all the supporting material for siting and of the environmental consequences of a deep repository.

3.3.2 Products after initial site investigation

After an initial site investigation, the available information on the geoscientific conditions at depth is still relatively limited. The task in this phase is to decide whether it is reasonable to proceed with a complete (more detailed) site investigation, or whether the site in question should be abandoned in favour of another site.

The *preliminary site description* is expected to contain a compilation of the general field studies that have been carried out in a given candidate area. The compilation is expected to include a description of the regional conditions around the area, plus an account of collected data and interpreted parameters for the limited in-depth investigations that have been carried out on the priority site.

The *preliminary facility description* will focus on describing alternative proposals for a preliminary layout of the deep repository. In this phase, however, there is only limited opportunity to adapt the facility to the rock's actual conditions and properties.

As far as long-term safety is concerned, the body of material available after the initial site investigation is not expected to be sufficient to conduct a comprehensive safety assessment. The *preliminary safety judgement* will therefore mainly contain:

- a cross-check with the requirements and criteria that have been formulated /Andersson et al, 2000/,
- comparisons with the conditions on the three sites that were analyzed in SR 97 /SKB, 1999a/ and what can thereby be said about expected analysis results, and
- simple analytical transport calculations of the kind that was carried out in SR 97, with whatever new site-specific data are available.

3.3.3 Information flow during a site investigation

Figure 3-4 illustrates in a highly simplified fashion the extensive exchange of information that takes place between the three principal technical activities during a site investigation. The solid arrows between the three activities symbolize the hierarchy of the exchange of information, where all products from investigations and design (*site description* and *facility description*) can be said to underlie the main product of the safety assessment: the *safety report*. The dashed arrows in Figure 3-4 symbolize the great need for feedback from design and safety assessment to investigations. Consequently, the execution of the investigations should be both logical, with a view towards the different main activities' data needs and decision-making junctures, and dynamic, in view of the specific conditions encountered on the sites and the results that are obtained as the investigations progress.

As pointed out previously, site investigations will be conducted on at least two sites. The important coordination function, whose purpose is to coordinate between different principal activities and different sites, is illustrated in the centre of Figure 3-4.

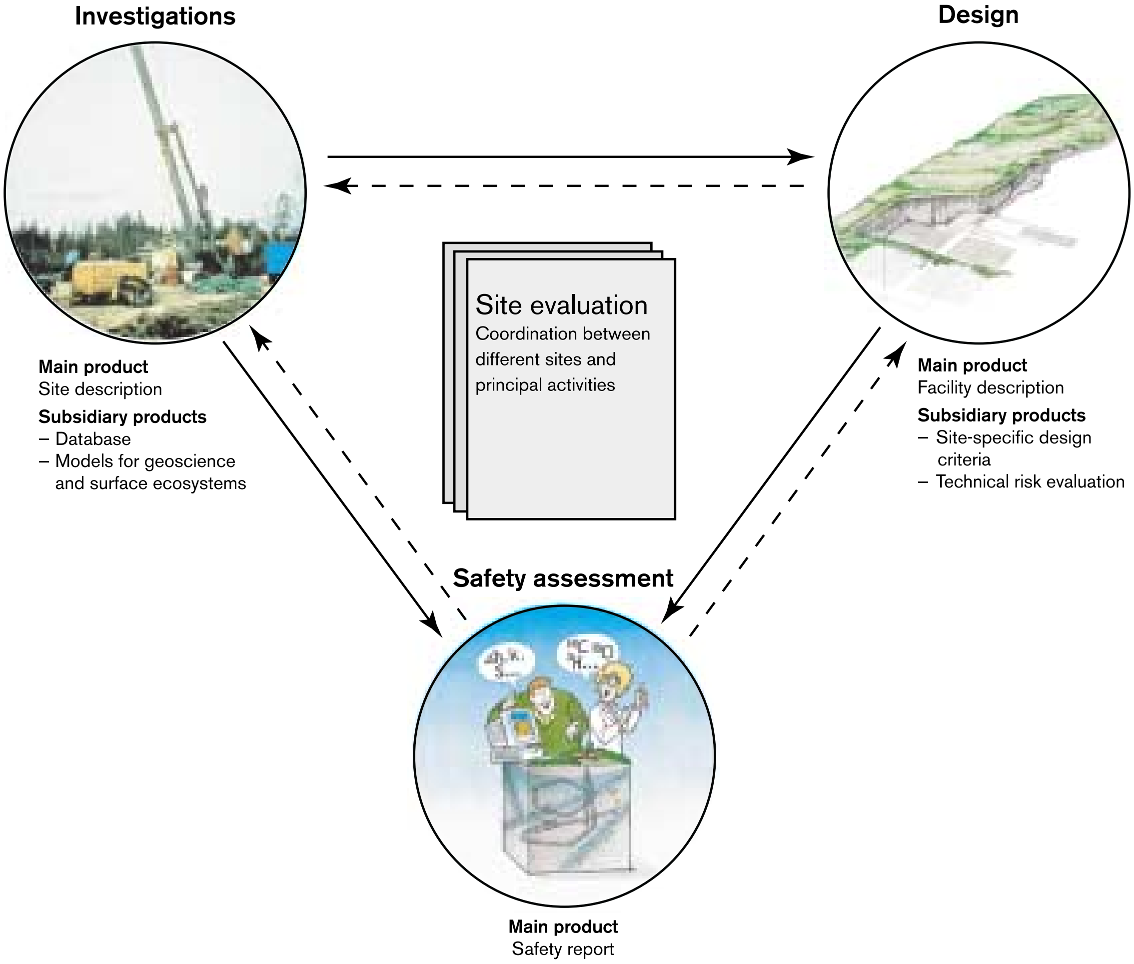


Figure 3-4. *Illustration of exchange of information between the three principal activities investigations, design and safety assessment. The important coordination function between different principal activities and different sites is illustrated in the centre of the figure.*

4 Investigations

This chapter describes the technical content of the investigations that are planned for the site investigation phase. The investigations are supposed to provide the necessary data for a site-adapted layout of the deep repository and for assessment of its long-term radiological safety. The investigations comprise the following steps: inventory, planning, field work, interpretation, documentation and archiving. The measurements normally yield information on conditions in individual measurement points. The measurement information therefore needs to be evaluated using different interpretation methods to enable the entire rock volume to be described (modelled). This description is in turn used by the activities *design* and *safety assessment*. Evaluation of the sites is described in greater detail in Chapter 5.

4.1 Strategy for the investigation programme

When the site investigations are finished, the activity *investigations* should have:

- presented the data on the site needed for a site-adapted layout of the deep repository and an assessment of the long-term radiological safety of the deep repository to be carried out.

Based on this general goal, a decision is made of what is to be investigated and how comprehensive the investigations are to be. The final plan for the investigation programme must, however, be adapted to conditions on the actual sites. The description presented here is mainly intended to provide a general picture of what elements and what types of investigations will be included. The activity *investigations* also includes geoscientific modelling, which is described in section 5.1.

4.1.1 What is to be determined?

SKB has conducted several studies – mainly the "Parameter report" /Andersson et al, 1996/ and the report on requirements and criteria /Andersson et al, 2000/ – to ascertain what site-specific information is needed to carry out safety assessment and design during the site investigation phase. The choice of parameters that need to be determined is based on SKB's long experience from rock investigations, including the Äspö Hard Rock Laboratory (HRL), and from various performance and safety assessments that have been conducted. The data need has in particular been cross-checked against experience and conclusions from SKB's most recent safety assessment, SR 97 /SKB, 1999a/.

In order to find out whether the investigated site satisfies the fundamental requirements made on the rock and to what extent the site satisfies formulated preferences, the investigations shall especially determine the following:

- the distribution and homogeneity of the rock types, and in particular whether such valuable minerals occur within the investigated volume that this could justify mining at a depth of hundreds of metres,
- location of regional plastic shear zones and location of regional and local major fracture zones,

- statistical description of fractures and local minor fracture zones,
- initial rock stresses and distribution of the mechanical properties of the rock and the fractures (strength, deformation properties and coefficient of thermal expansion),
- the rock's thermal conductivity and natural temperature conditions at repository depth,
- statistical distribution of permeability (hydraulic conductivity) on a deposition hole scale within the planned deposition areas,
- statistical distribution of groundwater flux (Darcy velocity) on a deposition hole scale within the planned deposition areas,
- permeability and assessment of possible technical construction difficulties related to the fracture zones that need to be passed during the underground construction work,
- the natural hydraulic gradient conditions at repository level,
- chemical parameters that indicate the absence of dissolved oxygen in the groundwater, i.e. redox potential, occurrence of divalent iron, or occurrence of sulphide,
- total salinity of the groundwater,
- pH, concentration of organic substances, colloid concentration, ammonium concentration, concentration of calcium and magnesium and concentrations of radon and radium,
- statistical description of the transport resistance of flow paths from the deposition area,
- statistical distribution of matrix diffusivity and matrix porosity along conceivable flow paths, and
- description of surface ecosystems and other ground conditions.

Besides these parameters, additional parameters need to be determined to obtain a good understanding of the site. Additional information on ground conditions etc is needed to design the repository's surface facilities and to enable access tunnels to be constructed outside of the actual repository area. The parameters that will be determined are shown in tables presented further on in this chapter. A more detailed account is given in the coming detailed characterization programmes.

The integrated assessment of whether a site is suitable is based to a high degree on the results of the design work and the safety assessment. The site is accepted only if a deep repository can be presented that is well-adapted to conditions on the site and the safety assessment shows that this repository is safe. Furthermore, the feasibility of the construction work must have been demonstrated, along with the fact that both the facility in itself and its construction entail an acceptable impact on nature, human culture and the rest of the environment. During a site investigation, when measurement values have been obtained from repository depth but before the overall assessment has been carried out, criteria are used to check whether requirements and preferences can be satisfied /Andersson et al, 2000/. The criteria provide guidance on the outcome of the assessments, but do not take their place.

4.1.2 Stages of the investigations

Site investigations will be carried out on at least two sites and are of such a large scope in terms of time, space and content that a suitable subdivision into stages is necessary. The subdivision must be logical and governed by the data needs of the main activities at different decision-making junctures, at the same time as it must permit rational execution of the investigations and minimize environmental disturbances. The site investigations are divided into the two main stages *initial site investigations* and *complete site investigations*. The overall purpose of these two stages is described in section 3.2. This subdivision into stages (and the iterative investigation methodology that is planned) has been applied by SKB in all study site investigations and during the pre-investigation phase for the Äspö HRL (see e.g. /Rhén et al, 1997/).

Initial site investigations

During the initial site investigations phase, each candidate area is investigated in order to:

- provide a basis for a fundamental understanding of the rock and the surface ecosystems on a regional scale,
- provide a basis for choosing a priority site for continued investigations, and
- with the aid of in-depth investigations in a limited number of boreholes on the priority site, collect information that makes it possible to determine whether the priority site is favourable for a deep repository and thereby suitable for complete site investigations.

The point of departure for the initial site investigations will vary a great deal, depending on the size of and the level of knowledge concerning the designated candidate areas. The initial investigation programme for investigations will thereby be different for different candidate areas. At a size of up around a couple of hundred square kilometres, or where the level of geoscientific knowledge is low, it may for example be suitable to carry out the geographic area restriction by identifying and studying several potential sites, see Figure 3-1.

The site where the complete site investigations are then to be concentrated, and for which the site descriptions are to be written, will be on the order of 5–10 km^2. This is required to provide room for all parts of the underground facility and to enable the environs of the repository area to be characterized as well.

Initially, the investigation activities are dominated by general field studies (mappings, inventories and surface geophysics) over the entire candidate area. When a priority site has been chosen, a limited number (2–3) of deep cored boreholes are drilled and investigated. The evaluation of the results from the initial site investigation, and the assessment of whether the priority site is suitable, are described in Chapter 5.

Complete site investigations

Provided that the initial site investigation shows that the priority site is favourable, as well as suitable from other aspects, complete investigations are commenced. During the complete site investigations stage, the investigations are aimed at:

- completing the characterization of the priority site and its environs by means of downhole investigations in an appropriate number of boreholes so that, if the site is found to be suitable, design and safety assessment can produce the supporting material required for a siting application.

The scope of the investigations can therefore only be determined site-specifically and in consultation with the primary beneficiaries: design and safety assessment. SKB estimates that the complete site investigation should comprise between 10 and 20 cored boreholes on each site, plus at least as many percussion boreholes. A rational execution of drilling and investigation require drilling and investigating a limited number of boreholes (3–4) in each campaign. The different investigation campaigns do not differ much from each other. However, new boreholes are drilled where the previous investigations show more information is needed.

4.1.3 Structure of the investigation programme

The investigation programme is structured discipline-specifically, partly in order to obtain a better overview, and partly to rationalize the practical execution of the programme. The programme is based on previous experience, see e.g. /Almén (ed), 1994/. At present, detailed discipline-specific programmes are being developed for the following seven disciplines:

- surface ecosystems,
- geology,
- hydrogeology,
- hydrogeochemistry,
- rock mechanics,
- thermal properties, and
- transport properties of the rock.

Of these, surface ecosystems, geology, hydrogeology and hydrogeochemistry, as well as rock mechanics to some extent, are the disciplines that dominate the field investigations. Most measurable thermal parameters are obtained from the geological investigations. Measurement data that provide a basis for determining transport properties are obtained above all from hydrogeology and hydrogeochemistry, but certain specific investigations of transport properties are also included in the programme. Geophysics is not a discipline of its own, but provides important data support to other disciplines. A programme for geophysical investigations will therefore be included in the discipline-specific programme *geology*.

4.2 Scope of the investigations in different stages

In order to create an overview, the following sections describe the principal scope of the investigations in the initial and complete site investigation stages. The investigation methods are described in greater detail in section 4.3.

4.2.1 Initial site investigation

General geological and hydrological mapping

The geoscientific investigations consist to begin with primarily of surface-based investigations conducted on the ground and from the air for the purpose of placing the investigation area in its regional context and selecting a priority site. The field investigations are initially dominated by an overall geological mapping and geophysical measurements.

Which geophysical measurements are to be performed depends on the content of the geophysical database taken over from the feasibility study. If airborne geophysical maps are lacking, such a measurement programme should be carried out. As an example, it can be mentioned that magnetic and radiometric methods can be used for the description of rock types. Magnetic methods can, along with electromagnetic methods, also be used to identify regional and local major deformation zones.

Lineament interpretation from digital topographical databases is often a good method for identifying the area's regional deformation zones, and is a complement to interpretation of airborne geophysical maps. Seismic refraction is an example of a ground geophysical method that can be used to check in the field the preliminary interpretations of the region's major structures. Examples of other surface geophysical methods that may be used in the initial site investigation are gravimetry, by means of which major rock units of varying density (e.g. granite bodies or greenstones) can be identified, and resistivity measurement, by means of which the bulk resistivity of different rock units can be determined. This property is dependent on the porosity of the rock, which in turn reflects its fracture frequency.

To assess the possible occurrence of neotectonic movements, it is checked whether such indications can be detected in conjunction with the geological mapping. Analysis of geodetic data from GPS networks and precision levellings are examples of other methods that can be used for the purpose of studying possible slow tectonic movements. Furthermore, it is judged to be advisable to establish a seismological observation grid at an early stage, even though such registrations are not expected to yield directly useful site-specific data. The reason for this is that seismic events of appreciable magnitude will probably not occur /SKB, 1999a/ during the relatively short span of time when the site investigations will take place.

If a large or predominant portion of the rock surface is covered with soil, the information that can otherwise be obtained by mapping of the rock surface must at least in part be replaced by sampling via short-hole drilling to the rock surface. Together with soil sounding, such drilling is also used to determine soil strata and soil depth. Geophysical methods such as ground radar can also be used to map soil strata and the location of the rock surface.

A percussion drilling programme will be required to answer specific questions, such as the dip of major fracture zones. The information can then be obtained from a maximum depth of about 200 m.

Surface water and groundwater conditions and chemistry are mainly studied by means of hydrological mapping, inventory and sampling of watercourses, springs and existing wells. During the feasibility study phase, such analyses were limited to existing data in the well archive kept by the Geological Survey of Sweden (SGU). It is further essential to take reference water samples in boreholes if drilling takes place. This is particularly true of newly drilled boreholes, since it is the only time sampling can take place under virtually undisturbed conditions.

Furthermore, a monitoring programme is being established for all hydrological and meteorological parameters that should be recorded over the long term. Examples of parameters of interest are the groundwater table in the area, deeper groundwater hydraulic heads, precipitation, temperature, potential evaporation and runoff in watercourses. All of these parameters normally exhibit both seasonal fluctuations and yearly variations, which means that the earlier the recordings are started the more complete the database will be within the investigation area.

Mapping of ecosystems

When the candidate areas have been identified, the work of inventorying and compiling available information on the surface ecosystems is also begun. It is above all important to compile available information from biotope and vegetation mappings, aerial photography interpretations and satellite imagery at an early stage to identify areas that require special nature conservation considerations. Locations of roads and to some extent drilling sites are planned on the basis of the compiled information. If areas classified as particularly sensitive to disturbances are likely to be affected, detailed inventories are first carried out in order to minimize any environmental impact. A simple field check is made in unclassified areas before any invasive procedures are performed.

The general biotope and vegetation maps also serve as a basis for decisions on where more thorough field checks and inventories must be carried out. The purpose is to create a detailed map with areas that require special consideration with regard to environmental impact, e.g. special key habitats and breeding grounds. Furthermore, favourable areas for beginning long, undisrupted measurement series of above all parameters in the aquatic environment, but also soil, can be identified. After field check and evaluation at an early stage, long-term measurements can start of water chemistry, hydrology, and fauna and flora.

Long-term series of such measurement data provide a baseline for undisturbed conditions and for an understanding of seasonal variations in the area. They also make it possible to evaluate any environmental impact of the site investigation. Some of these measurement series will also serve as a basis for environmental monitoring, which can continue in the event of detailed characterization.

Investigations on a priority site

Continuation of the initial site investigation is predicated on the selection of a priority site within the candidate area. It is not until now that exploratory drilling is carried out to great depth. It is then essential to begin by investigating parameters that are sensitive to disturbances and conditions that could directly determine that the priority site cannot be accepted or that it is clearly unsuitable for a deep repository (see /Andersson et al, 2000/). A drilling and investigation programme that comprises a few (2–3) deep cored boreholes and a number of percussion boreholes is therefore carried out with these primary aims.

Even if the number of boreholes is limited during this phase, the investigation programme will be extensive so that any spatial variations in the properties of the bedrock can be analyzed. The thrust of the downhole investigations is described in greater detail in section 4.3.

The rock's deformation zones are among the most crucial properties of the bedrock in determining the layout of the repository's rock caverns. The zones occur in all sizes and require intensified investigation activities as requirements on detailed knowledge of the bedrock increase. The goal of the geoscientific investigations here is preliminary identification of deformation zones that are not allowed to occur in the vicinity of the deep repository, as well as those that can be allowed to pass between the repository areas, see further Chapter 5. This means that in particular all regional and most local major fracture zones, in accordance with SKB's geoscientific nomenclature for deformation zones in rock (see section 5.1.2), must be identified and characterized.

The drilling will probably be preceded by seismic reflection surveys comprising intersecting profiles a couple of kilometres in length. This method is able to indicate the presence of major subhorizontal deformation zones at depth, which is essential knowledge prior to the start of drilling, since flat-lying zones can restrict the utilization of the rock if they occur at an unsuitable depth and have unfavourable properties. The outcome of the seismic reflection measurements may be used for detailed planning of the continued drilling and investigation programme, even though the properties of any zones cannot be established until drilling and measurement at a later point.

Examples of other ground geophysical profile surveys that can also be conducted to augment the geological-structural characterization are above all magnetic and electromagnetic methods. Electric sounding and transient electromagnetic sounding can be used to trace resistivity changes with depth, which may be due to the presence of major subhorizontal fracture zones or more saline groundwater. The extent of the zones or the saline water over a larger area can be determined, particularly if the results can be calibrated against sampling in a borehole.

Data for identification and interpretation of deformation zones are obtained from geological and geophysical measurements in the aforementioned boreholes and by drilling of shorter holes, specially intended for determining the dip of fracture zones emerging on the surface. One of the deep holes drilled in this phase should preferably be positioned close to the point of intersection of the seismic reflection profiles, which should if possible be taken into consideration when these profiles are laid out. Vertical Seismic Profiling (VSP) should preferably be carried out in this hole, which should be subvertical and nearly 1,000 m deep. Co-interpretation of VSP and seismic reflection provides a good means for characterization of the occurrence of deformation zones in a relatively large rock volume.

Rock type distribution and the zones of less importance for rock cavern layout are determined in detail in each borehole. Furthermore, the rock surface will be exposed along intersecting profiles (if possible at the seismic reflection profiles) and/or on a larger area. The purpose is to obtain a good picture of rock type distribution and good statistics on the geometric properties of fractures such as trace length, orientation and frequency. The size of fractures cannot be measured in boreholes.

Drilling of the first deep borehole also entails the first deep disturbance of the groundwater conditions. It is therefore essential to carry out an optimal hydrogeological and hydrochemical sampling programme in this particular hole. The chemistry programme determines not only the sampling and analysis methodology, but also the drilling procedure as such in order to obtain undisturbed water samples in a controlled manner, both during the actual drilling and in the subsequent sampling programme. An example of a key hydrogeochemical parameter belonging to the category that is sensitive to disturbances is the redox potential (Eh). Oxidizing conditions and/or occurrence of dissolved oxygen at repository depth are examples of hydrogeochemical situations that cannot be accepted. While such conditions are not expected to exist at a depth of several hundred metres, the groundwater in the first borehole must be carefully checked before it is subjected to further disturbance. Another important parameter that should also be determined in the first borehole is the groundwater's total salinity (TDS = Total Dissolved Solids), since high concentrations can affect the suitability of the site /Andersson et al, 2000/.

In the hydrogeological programme, the permeability of the rock mass and the deformation zones is determined by means of hydraulic tests, which are performed with the guidance of the geological-structural information obtained in conjunction with drilling.

Rock stress measurements are above all performed using the overcoring method, which is done in conjunction with drilling, preferably at several levels down to planned repository depth. As a complement to the overcoring method, hydraulic fracturing will probably also be performed in the same borehole in a large number of measurement points between depths of 100 m and 800 m. However, since water is injected in this method, these measurements must wait until all water sampling and sensitive hydraulic tests have been carried out. High rock stresses, particularly in combination with considerable anisotropy (directional dependence) and/or low rock strength can be indicated during core drilling by the occurrence of core discing, entailing cracking of the drill core into discs. This phenomenon is good as an indicator, but not adequate to determine with certainty whether unsuitable stress conditions or strength properties exist.

The long-term monitoring that was initiated previously is continued and extended. All new investigation boreholes are packered for registration of pressure conditions in the deeper groundwater as soon as the downhole measurements have been carried out.

4.2.2 Complete site investigation

The complete site investigation stage is supposed to provide the information needed to assess the suitability of the site and to compile the material needed in support of a siting application, see 4.1.1. The investigations will be dominated by drilling and various kinds of downhole investigations. The scope of the investigations in different disciplines is described in the method presentation in section 4.3.

The drilling programme will comprise a number of boreholes on each site. A rational execution of drilling and investigation necessitates drilling and investigating in groups of at least three boreholes. This minimizes the environmental disturbance caused by these activities. The investigation activities do not differ appreciably between the different drilling campaigns.

The evaluation of the information that is available at various points in time is allowed to determine where new boreholes are to be located to some extent. As a general rule, however, the boreholes should be suitably distributed over the whole site, both horizontally and vertically, with the goal of achieving the same level of geoscientific knowledge for the entire model area, but with a higher degree of detail for those parts deemed to be most likely for the location of deposition areas. Boreholes can also be positioned to investigate purely construction-related questions, e.g. to determine the best location for access tunnels outside of the actual repository area.

The investigations must naturally not be allowed to adversely affect the long-term properties of the site. However, this does not comprise a primary restriction on where the boreholes can be positioned. Decisions as to which boreholes are to be plugged when the repository has been sealed and which should be kept open for long-range registration are made at later stages of repository construction, or when the repository is to be closed. However, the locations of the boreholes are determined very accurately so that it will be possible to take them into consideration during design and safety assessment.

Neither design nor safety assessment require deterministic knowledge of the properties of the rock in all respects after completed site investigation. For several parameters it is enough to ascertain a statistical distribution. Even a small number of boreholes provides good information on the site's major fracture zones and on the statistical distribution of rock properties. Additional boreholes provide information on minor fracture zones and more detailed knowledge of the spatial variation of the properties. When the uncertainties have been sufficiently well determined, there is no reason to drill more boreholes, even though this would provide limited additional information. Moreover, it is much easier to obtain more detailed knowledge of many parameters in the subsequent detailed characterization from repository depth. Other parameters cannot be determined at all by boreholes from the surface, but require measurements from tunnels.

It is not possible to say in advance how many boreholes will be needed to achieve sufficient knowledge. The scope of the investigations will depend on how complex the site is and how the boreholes are positioned. A more heterogeneous site with many fracture zones needs more boreholes than a homogeneous site. A few horizontal boreholes through the repository area can provide a great deal of information under certain circumstances, but are much more difficult to drill. The scope of the investigations can therefore only be determined site-specifically and in consultation with the primary beneficiaries: design and safety assessment. Nevertheless, SKB estimates that the complete site investigation may comprise between 10 and 20 deep boreholes.

Mapping and surveys on the ground surface also continue during the complete site investigation, mainly for the purpose of supplementing previous ground investigations and answering specific questions from the initial site investigation. It is then mainly a question of obtaining further details in the geological mapping and performing detailed geophysical measurements. These surveys are mainly concentrated to the priority sites. The regional environs will also probably be the subject of supplementary investigations in this phase.

4.3 Investigation methods

The following sections present brief discipline-related accounts of what a (typical) site investigation can entail. For each discipline, a table is presented showing which parameters are included and in which phase they will mainly be determined. These accounts will be further elaborated on in conjunction with SKB's presentation of discipline-specific programmes at a later time. For a more detailed presentation of the various investigation methods, see the Appendix. There they are presented in a table together with a compilation of what information can be determined.

4.3.1 Surface ecosystems

Mapping of ecosystems is largely done by *compiling already available information* from biotope and vegetation mappings, aerial photography interpretations and satellite imagery. Based on these sources, more thorough field checks and inventories of flora and fauna will be accomplished.

Field checks and *inventories* are non-invasive, involving only visits by ecologists and biologists. These activities are conducted entirely during the site investigation on the priority areas.

Water samples and *soil samples* are taken in various areas. Chemical and biological composition is determined in the laboratory. The invasive procedures are normally minor, but sample series will be taken over a long period of time.

A detailed *mapping of potential discharge areas* is performed with respect to dominant ecosystems and unconsolidated deposits (organic and mineral soil). If the priority site is situated at or near the coast, the bottoms are mapped in relevant coastal areas. This provides a basis for surface hydrological models in present-day and future discharge areas.

The development of the ecosystems and the loose deposits is determined by means of *sedimentation measurements* and *growth measurements* in the form of dating of the stratigraphy together with historical data on the area. This information also provides a more detailed picture of shore line displacement in the area. Measurements of *water flows and water turnover* provide data for determining the flow of materials through the ecosystems to man and the environment. In a later phase, *production measurements in the field* are carried out based on e.g. vegetation and biotope maps produced and quantity estimates.

The surface ecology parameters to be determined during the site investigation phase are summarized in Table 4-1.

Table 4-1. Compilation of surface ecology parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC). Further relevant parameters are found in other discipline tables.

Parameter group	Parameter	Determined primarily during			
		FS	ISI	CSI	DC
Forestry	Quantity		x	x	
	Production		x	x	
	Rotation		x	x	
	Age structure	x	x		
Agriculture	Production, crops		x	x	
	Animal husbandry, meat production		x	x	
	Number of farms	x	x		
	Position	x	x		
	Area	x	x		
Fishing/hunting	Fishing licences, number	x	x		
	Catches	x	x		
	Professional fishermen, number	x	x		
Outdoor recreation	Berry and mushroom picking			x	

Parameter group	**Parameter**	**Determined primarily during**			
		FS	**ISI**	**CSI**	**DC**
Climate	Ground frost, number of days and depth		x		
	Ice formation and break-up		x		
	Wind force and direction			x	
	Air pressure			x	
	Sunshine, hours of daylight, insolation and angle			x	
	Vegetation period			x	
Deposits	Soil, type and thickness		x	x	
Toxic pollutants and radionuclides	Radionuclides in biomass		x		
	Toxic pollutants in biomass		x		
Flora	Type of vegetation	x	x		
	Key habitat	x	x		
	Population		x		
	Production		x	x	
	Species of vascular plants, fungi, lichens mosses and algae		x		
	Red-listed species		x		
Fauna	Species and number (mammals, reptiles and birds)		x		
	Biomass		x		
	Production		x	x	
	Red-listed species	x	x		
Lakes and watercourses	Lake types		x		
	Sediment type		x		
	Oxygen content		x		
	Oxygenation		x		
	Stratification		x		
	Light conditions		x		
	Temperature		x		
Sea	Water turnover		x	x	
	Currents		x	x	
	Degree of exposure (shore)		x		
	Sediment type		x		
	Oxygen content		x		
	Oxygenation		x		
	Stratification		x		
	Light conditions		x		
Supporting data	Surface geology		x	x	
	Surface hydrogeology		x	x	
	Surface hydrogeochemistry		x	x	
	Surface transport properties		x	x	

4.3.2 Boreholes and downhole investigations

Each borehole is drilled for a more or less specific purpose, for example to provide fundamental information on geoscientific conditions for a certain portion of the rock volume or to verify the occurrence of fracture zones or rock type boundaries and geometrically determine their position and/or orientation. The scope of the drilling programme cannot be specified in advance, since it will depend greatly on such conditions on the site such as soil cover and rock homogeneity.

Percussion boreholes are normally drilled down to a maximum of 200 metres and cored boreholes usually to a depth of between 500 and 1,000 metres. The boreholes are normally oriented between vertical (90°) and 50° from the horizontal plane. There may be reason to drill short cored holes, just as it may be found necessary to drill holes deeper than 1,000 metres on the priority site or in the regional environs.

Of the aforementioned borehole types, *cored boreholes* give most information for the geoscientific characterization. All deep cored holes will probably be drilled with the wireline technique, whereby the drill core is lifted up by means of a wire and the drill string only needs to be lifted out when the bit needs to be changed.

Experience from the Äspö HRL will be utilized to limit the negative effects of the flushing water's penetration into the rock formation under high pressure /Almén and Zellman, 1991/. Thus, core drilling will be carried out using the telescopic drilling method, whereby the uppermost 100 metres of the borehole has a larger diameter, and airlift pumping is used in this upper part of the hole to reduce the amount of flushing water and drill cuttings that penetrate into the rock. Furthermore, the flushing water will be taken from a borehole nearby and stored in tightly closed pressurized tanks to prevent oxygen from dissolving in the water. Before the water is used as flushing water, it is marked with the tracer uranine.

Different *flushing water parameters* (flushing water flow, flushing water pressure, return water flow, uranine content and drawdown) and drilling parameters (mainly drilling rate) will be recorded. These data provide early information on, for example, whether water-bearing or major fracture zones are penetrated, which is significant in deciding when to make interruptions for water sampling and hydraulic testing. These recordings also provide a good opportunity for calculating how large a fraction of the flushing water has remained in the rock.

Water sampling during drilling will thus be performed above all when water-bearing fracture zones and individual major fractures are penetrated (which can be indicated by flushing water parameters and drill core). As a complement, water samples can be taken at regular intervals, for example every 100 metres. As mentioned previously, the groundwater chemistry is very sensitive to disturbances, not least via contamination by admixture with alien water from the surface or from other parts of the bedrock, caused by the borehole acting as a hydraulic short-circuit. The longer time has passed since drilling, the further into the fracture systems contamination can take place. Water sampling directly during drilling is considered to be the best method for obtaining undisturbed groundwater samples, since the short-circuiting effect of the borehole has then acted only for a very short time. Sampling during drilling requires the use of appropriate and robust sampling methodology and equipment. Drilling with the wireline technique enables both water sampling and hydraulic testing to be carried out in a more time-efficient manner, since the testing and sampling equipment can be lowered down into the drill string.

When sampling is performed during drilling, the analysis programme is limited to a smaller number of chemical parameters. This means that sampling during drilling can never take the place of the more complete chemical characterization that will be performed later. Water sampling during drilling will be combined with simpler hydraulic tests.

Even if the starting direction of the borehole has been carefully set, it is normal for a borehole to deviate slightly from the planned direction. This deviation may, for example, be caused by the bedrock's foliation, predominant fracture directions or other mechanical anisotropy in the rock mass. Borehole deviation is measured by means of special borehole probes. In boreholes whose direction is particularly important, deviation should be measured and adjusted regularly during ongoing drilling (controlled drilling).

Aside from good knowledge of the deviation of the borehole, it is essential to know exactly how deep (or rather at what borehole length) each measurement in the borehole is being made. This is particularly important when several parameters are being co-interpreted. SKB has developed a method for length calibration where reference grooves that can be detected in subsequent measurements are cut into the borehole wall during drilling.

The typical investigations described in the following are mainly carried out in cored holes, while the investigations in the percussion holes are usually limited to a smaller number of methods, mainly because these holes are, to a higher degree than the cored holes, drilled for a specific purpose, e.g. to verify the dip of a fracture zone or to install packers for long-term monitoring of superficial groundwater hydraulic heads.

4.3.3 Geological and geophysical investigations

Surface-covering investigations

Geological bedrock mapping is done chiefly by studies of rock outcrops. Road cuts are also used, since the rock surfaces there often provide good information on rock types and fractures. Mapping of deliberately exposed surfaces can be used to obtain statistics on the orientation and lengths of fractures. Mapping of the soil cover is done using traditional methods where aerial photographs are used as a basis and sounding and sampling are done to determine Quaternary deposits, strata sequences and soil depths. Lineament interpretation from digital topographical databases is often a good method for identification of the area's regional fracture zones, and is a complement to interpretation of airborne geophysical maps. If *airborne geophysical surveys* are lacking, a measurement programme should be carried out. For example, magnetic and radiometric methods can be used for the description of rock types. Magnetic methods can, along with electromagnetic methods, also be used to identify regional and local major deformation zones.

An example of *ground geophysical surveys* that may be employed is *seismic refraction*, which can be used to check in the field the preliminary interpretations of the region's major steeply-dipping fracture zones. Seismic refraction is an example of a ground geophysical method that can be used to check in the field the preliminary interpretations of the region's major structures. Examples of other ground geophysical methods that may be used are *gravimetry*, by means of which major rock units of varying density (e.g. granite bodies or greenstones) can be identified, and *resistivity measurement*, by means of which the bulk resistivity of different rock units can be determined. This property is dependent on the porosity of the rock, which in turn reflects its fracture frequency. Other examples are *electric sounding* and *transient electromagnetic sounding*, which are used to trace resistivity changes with depth, which can be due to the presence of major subhorizontal fracture zones of relatively high porosity or more saline groundwater. The extent of the saline water over a larger area can be determined, particularly if the results can be calibrated against sampling in a borehole. *Seismic reflection* is used particularly to trace the possible occurrence of major subhorizontal fracture zones at depth, which is very difficult using ground-based methods. The occurrence of flat-lying zones is an important piece of knowledge, since they can limit the utilization of the rock if they occur at an unsuitable depth and have unfavourable properties. The method also provides good material for interpretation of the occurrence and orientation of other major subhorizontal fracture zones at depth, although not their properties, which must be determined by drilling. The outcome of the seismic reflection surveys thereby comprises a good basis for detailed planning of the continued drilling and investigation programme.

Assessment of the possible occurrence of *indications of neotectonic movements* is done in conjunction with the geological mapping. Analysis of geodetic data from GPS networks and precision levellings are examples of other methods that can be used for the purpose of studying possible slow tectonic movements. Furthermore, it is judged to be advisable to establish a seismological observation grid at an early stage, even though such registrations are not expected to yield directly useful site-specific data for the reason that seismic events of appreciable magnitude will probably not occur /SKB, 1999a/ during the relatively short span of time when the site investigations will take place.

If a large or predominant portion of the rock surface is covered with soil, the information that can otherwise be obtained by mapping of the rock surface must at least in part be replaced by sampling via *short-hole drilling to the rock surface*. Together with soil sounding, such drilling is also used to determine soil strata and soil depth. Geophysical methods such as *ground radar* can also be used to map soil strata and the location of the rock surface. Conventional geotechnical investigations will be used to locate suitable ground conditions for surface infrastructure and establishment areas.

Downhole investigations

In the completed borehole, the *borehole wall is videotaped* using the BIP (Borehole Image Processing) system, after which geophysical loggings (radiometric, electric, magnetic and acoustic methods plus temperature) are performed, along with radar and seismic surveys, see Figure 4-1.

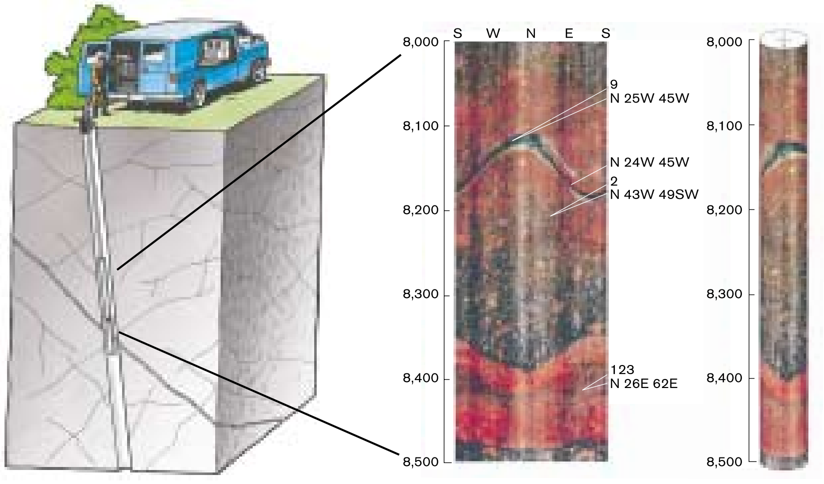


Figure 4-1. *BIP (Borehole Image Processing) is used together with borehole radar and other geophysical methods for characterization of rock types and structures.*

The base for the geological mapping along the borehole consists of the fact that the mapping of the drill core is integrated with the analysis of the BIP images from the video recording, a methodology called *BOREMAP*. The method is based on the fact that the geometric components (rock type boundaries plus location and orientation of fractures) are taken from the BIP image, while the information on rock types and properties of rock surfaces (fracture-filling minerals, surface structure, etc) is taken from the drill core.

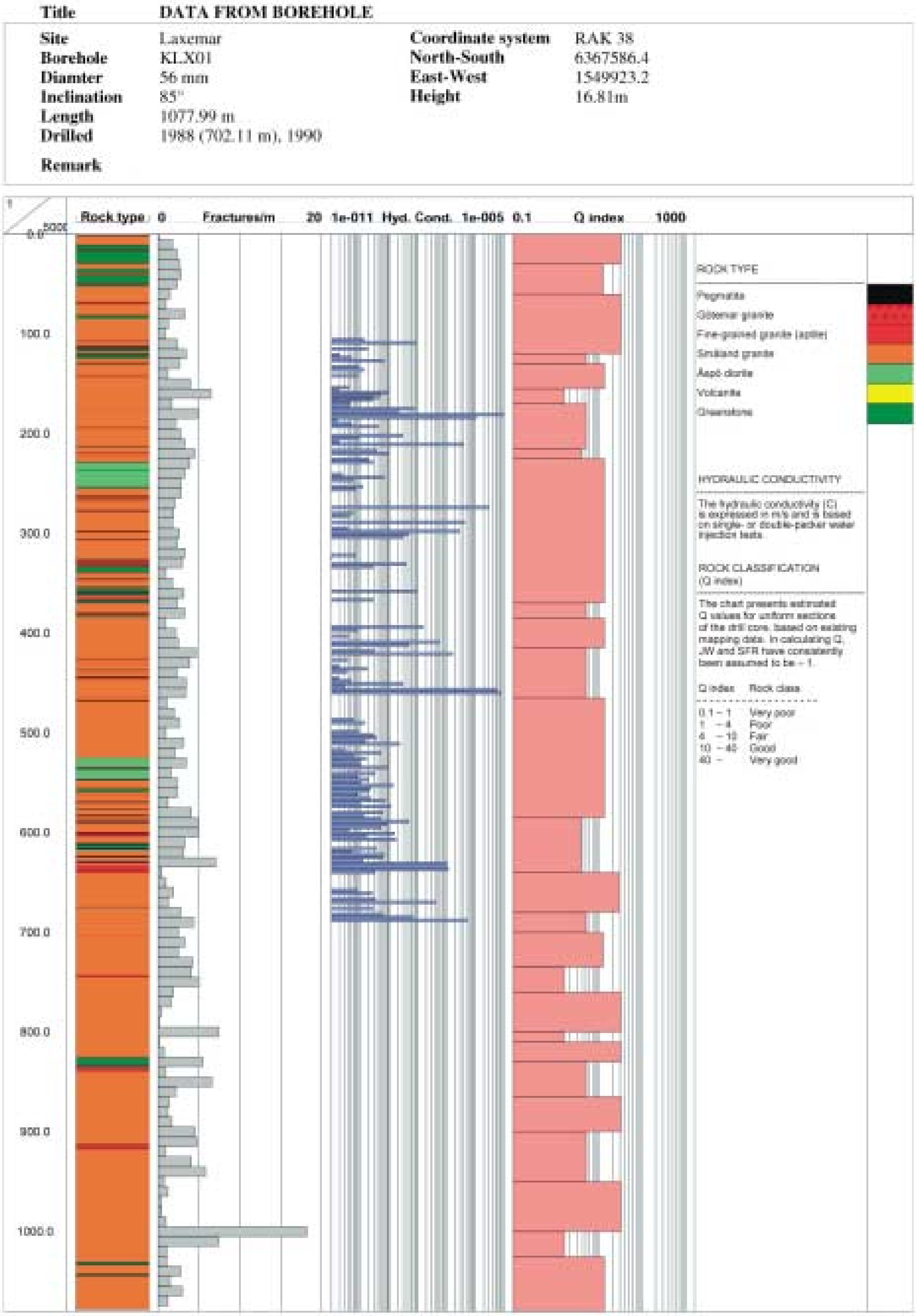
The geological characterization of the borehole is supplemented with *laboratory analyses of core samples*. Microscopic methods are used for analysis of rock types, fracture-filling minerals and chemical composition, while petrophysical methods are used for determination of density, porosity, magnetic susceptibility, etc. In connection with percussion drilling, the colour of the drill cuttings is checked and routine samples are taken for ocular inspection. Laboratory analyses are also performed when necessary.

The *geophysical borehole logs* provide supplementary indirect information on the physical properties of the rock. For example, the natural radioactivity of the bedrock is determined by its content of radioactive isotopes – mainly uranium, thorium and potassium – whose occurrence in turn depends on the petrological composition of the rock. Measurement of natural gamma radiation can help to find the boundaries between different rock types, which can sometimes be difficult with the naked eye. Other radiometric methods in which radioactive radiation sources are used are neutron (porosity) and gamma-gamma (density). Of electrical methods, resistivity methods are used to reflect variations in the fracture content of the bedrock along the borehole, whereby individual fractures can be detected or average porosity (bulk resistivity) determined, depending on how the electrodes are arranged geometrically in the borehole and on the ground surface. Other geophysical logging methods are sonic and magnetic susceptibility, as well as temperature and electrical conductivity of the borehole fluid. The geophysical logging results mentioned above provide supporting information for the mapping geologist, but are also used in hydrogeological and rock-mechanical interpretation.

Borehole radar is above all useful for locating and determining the orientation of local major and minor fracture zones, dikes etc within a radius of up to 100 metres from the borehole in favourable cases. *Seismic methods* have usually been used to detect similar structures at even greater distances, but then with poorer resolution. VSP (Vertical Seismic Profiling) has proved to be a suitable method for use in connection with seismic reflection surveys, whereby co-interpretation provides good opportunities to indicate the occurrence and extent of major fracture zones in a relatively large rock volume. The methods complement each other in the determination of structures, partly due to the aforementioned difference in range and resolution, but also because the methods utilize different properties in the rock (electrical and mechanical, respectively) and are therefore advantageous under different conditions.

In SKB's integrated system for *geological borehole documentation* (GBD), the results of the geological and geophysical investigations can be presented in composite charts with the aid of a customized WellCAD system (Figure 4-2). Any number of parameters can be presented, as well as statistically processed information. Hard copy printouts of a continuous BIP log of an entire borehole provide a very useful basic documentation of the borehole, and afford together with the GBD results a good visual impression of the borehole (Figure 4-1), of great use in planning different kinds of subsequent downhole measurements.

The geological parameters to be determined are summarized in Table 4-2.



Title DATA FROM BOREHOLE

Site	Laxemar	**Coordinate system**	RAK 38
Borehole	KLX01	**North-South**	6367586.4
Diamter	56 mm	**East-West**	1549923.2
Inclination	85°	**Height**	16.81m
Length	1077.99 m		
Drilled	1988 (702.11 m), 1990		
Remark			

ROCK TYPE

- Pegmatite ⬛
- Götemar granite 🟥
- Fine-grained granite (aplite) 🟥
- Småland granite 🟧
- Äspö diorite 🟩
- Volcanite 🟨
- Greenstone 🟩

HYDRAULIC CONDUCTIVITY

The hydraulic conductivity (C) is expressed in m/s and is based on single- or double-packer water injection tests.

ROCK CLASSIFICATION (Q index)

The chart presents estimated Q values for uniform sections of the drill core, based on existing mapping data. In calculating Q, JW and SFR have consistently been assumed to be ~ 1.

Q index	Rock class
0.1 – 1	Very poor
1 – 4	Poor
4 – 10	Fair
10 – 40	Good
40 –	Very good

Figure 4-2. *Example of presentation of geological borehole documentation (GBD) with the aid of WellCAD presentations. Any number of parameters can be presented.*

Table 4-2. Compilation of geological parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during			
		FS	ISI	CSI	DC
Topography	Topography	x	x		
Soil cover	Thickness of soil cover		x	x	
	Mineral soil distribution	x	x		
	Mineral soil description		x		
	Soil		x		
	Bottom sediment		x	x	
	Indication of neotectonics		x		
Bedrock					
Rock types					
Occurring rock types	Rock type distribution (spatial and percentage)	x	x	x	x
	Xenoliths			x	x
	Dikes	x	x	x	x
	Contacts		x	x	x
	Age			x	
	Ore potential – industrial minerals	x	x		
Rock type description	Mineralogical composition		x	x	x
	Grain size			x	x
	Mineral orientation			x	x
	Microfractures			x	x
	Density		x	x	
	Porosity			x	
	Susceptibility, gamma radiation etc		x		
	Mineralogical alteration/weathering		x	x	x
Bedrock Structures					
Plastic structures					
Folding	Extent/age		x	x	x
Foliation	Extent/age		x	x	x
Lineation	Extent/age		x	x	
Veining	Extent/age		x	x	
Shear zones	Extent/age	x	x	x	
	Properties	x	x	x	
Brittle structures					
Regional and local major fracture zones	Location	x	x	x	
	Orientation		x	x	
	Length	x	x	x	
	Width		x	x	
	Movements (size, direction)			x	
	Age			x	
	Properties (number of fracture sets, spacing, block size, fracture roughness, fracture filling (fracture mineral), weathering/alteration)		x	x	x

Parameter group	Parameter	Determined primarily during			
		FS	ISI	CSI	DC
Local minor fracture zones	Location/density		x	x	x
	Orientation			x	x
	Length		x	x	x
	Width			x	x
	Movements (size, direction)			x	x
	Age			x	x
	Properties (number of fracture sets, spacing, block size, fracture roughness, fracture filling (fracture mineral), weathering/alteration)			x	x
Fractures – data for stochastic description	Density (different sets)		x	x	x
	Orientation		x	x	x
	Trace length		x	x	x
	Contact pattern			x	x
	Aperture width			x	x
	Roughness			x	x
	Weathering (alteration)			x	x
	Fracture filling (fracture mineral)			x	x
	Age			x	x

4.3.4 Hydrogeological investigations

The hydraulic property that requires the greatest investigation effort is the permeability of the rock to water. Normally, permeability in the rock mass is represented by the parameter hydraulic conductivity, while permeability in the fracture zones and major fractures that are regarded as individual flow elements is represented by the parameter transmissivity. The transmissivity of a fracture zone is equal to its hydraulic conductivity multiplied by the thickness of the whole zone. The permeability of the zones, expressed as hydraulic conductivity, is normally two to three orders of magnitude greater than that of the rock mass.

The permeability of the rock mass and the zones is determined by means of *hydraulic tests*, where the prevailing pressure level in the rock formation is disturbed by water injection or pumping and the hydraulic response is measured, Figure 4-3. These tests are performed for the most part as *single-hole tests*, usually for one sealed-off borehole section at a time. The section is sealed off by means of rubber packers. Permeability is then determined section by section along the entire borehole. The tests are performed with borehole sections of different lengths in order to gain knowledge of the scale dependence of the permeability. Tests between two or more boreholes, known as *interference tests*, are performed to characterize individual fracture individual fracture zones or a whole rock volume on a larger scale.

Due to the spatial variation of the permeability, a relatively large number of measurements must be conducted systematically in boreholes to obtain good certainty in the statistical properties of this parameter in each investigation area.

The following investigations will be carried out during the site investigation phase, although all methods will not be used in all boreholes. Some of these hydraulic methods will probably be included in the aforementioned programme for borehole characterization, which will be further elaborated on in the discipline-specific programmes which SKB will present at a later time. The methods are presented in the order in which they will most often be used:

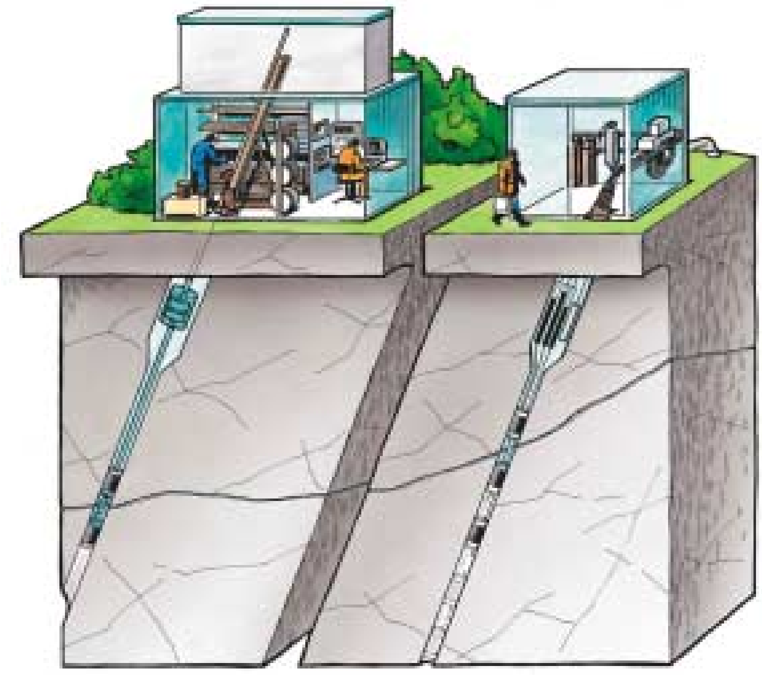


Figure 4-3. Examples of hydraulic tests.

Hydraulic tests in conjunction with drilling

Hydraulic tests in conjunction with drilling provide early information. These tests are usually conducted in conjunction with water sampling during drilling, i.e. when water-bearing fractures are penetrated and at uniform borehole intervals, e.g. 100 metres. They are performed as pumping tests. Furthermore, it is advisable to measure the groundwater's pressure level in conjunction with these tests, since the borehole's short-circuiting effect has not yet had time to propagate far out in the rock.

Pumping test in open hole and flow logging

A pumping test in an open hole gives an average value of the permeability on the borehole scale of 500–1,000 metres, while flow logging gives information on the distribution of water-bearing zones along the borehole as well as individual values for the major zones. Flow logging is combined with measurement of electrical conductivity and temperature, helping to fix the position of the water-bearing zones. Water samples are also taken to a suitable extent during the pumping test.

Hydraulic injection tests

Hydraulic injection tests are carried out by injecting water out into the rock in short borehole sections sealed off by rubber packers. The tests are performed systematically with suitable packer spacings. During the pre-investigations for the Äspö HRL, injection tests were performed in 30- and 3-metre-long borehole sections, of which the 30-metre tests were performed in three holes and the 3-metre tests in 8 holes. By studying the time dependence of the test results, information on the flow regime (linear, radial or spherical flow) can also be obtained, in addition to permeability. Figure 4-4 shows examples of results from injection tests in 20–25-metre-long borehole sections on SKB's

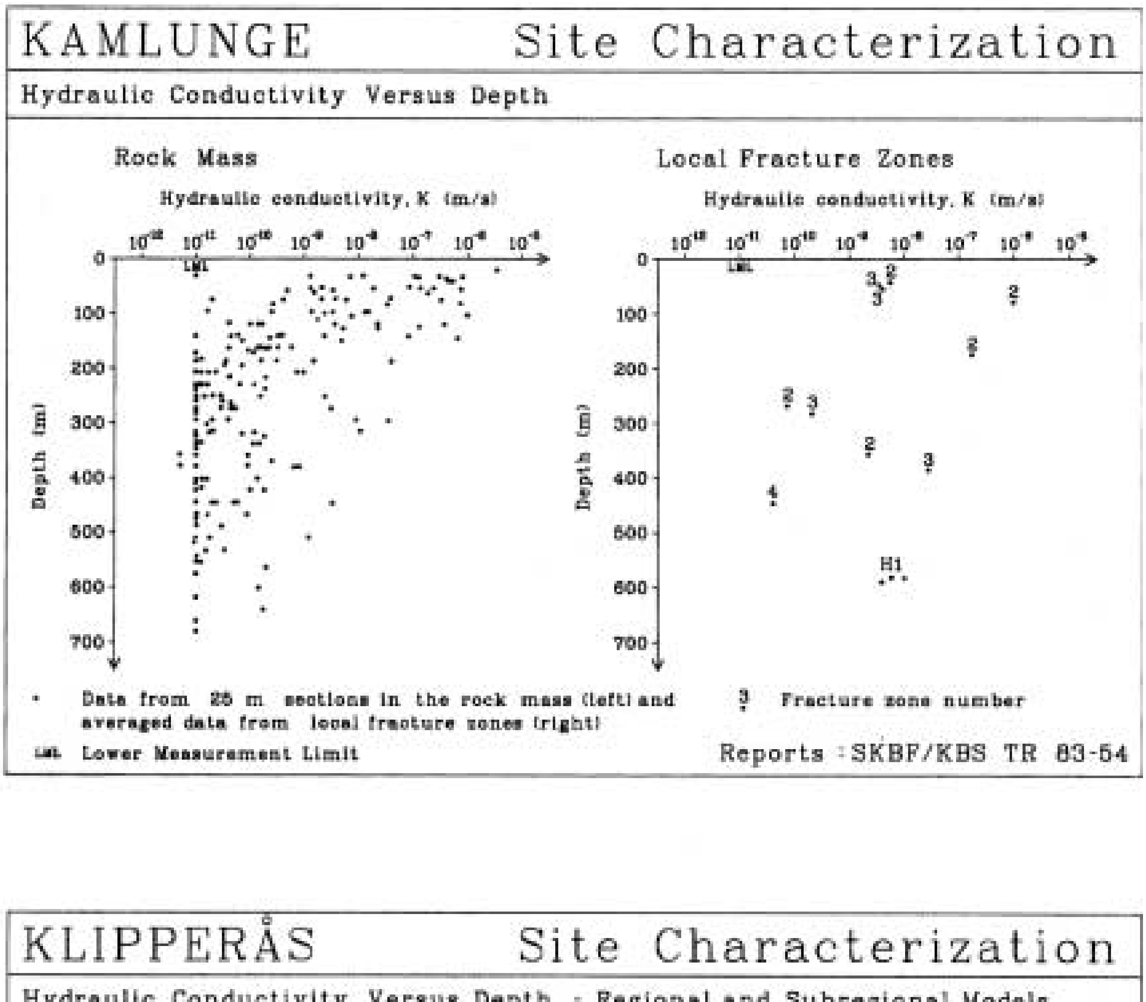


Figure 4-4. *Examples of results from hydraulic injection tests. The measurements stem from SKB's study sites in Kamlunge and Klipperås /Ahlbom et al, 1992a,b/.*

study sites Kamlunge and Klipperås. The question of which scales will be used in the site investigations will be dealt with in coming discipline-specific programmes for hydrogeology. The method may to some extent be replaced by differential flow logging.

Differential flow logging

In differential flow logging, the flow from a sealed-off borehole section is measured (in contrast to ordinary flow logging, where the cumulative inflow on the way up along the borehole is measured). In terms of results, the method can be regarded as something in between, or a combination of, flow logging and hydraulic injection testing. The method includes measurement at different pumping capacities, enabling permeability to be determined. A particularly detailed logging in short increments also provides information on the location of individual water-bearing fractures. The method is relatively fast and is expected to reduce the use of the more traditional and time-consuming injection tests.

Interference tests

Hydraulic tests in which pressure responses are recorded in a number of boreholes surrounding the one into which water is being pumped are called interference tests. Interference tests are used to determine the hydraulic properties of major water-bearing zones or units in the rock mass. The results provide information on e.g. hydraulic connectivity in the rock and are a valuable aid for calibrating hydraulic simulations in connection with numerical modelling (see section 5.1). SKB usually performs interference tests between packers and long-term interference tests in open boreholes.

During *interference tests with pumping between packers*, water is pumped from a major water-bearing fracture zone that has been sealed off with packers. Pumping takes place for a relatively long period of time (usually a couple of days) so that hydraulic head responses can appear in adjacent boreholes (observation holes). These observation holes are divided into several sealed-off borehole sections with associated recording instruments for measurement of hydraulic head. The purpose of these tests is to check/verify the structure's interpreted geometric extent and hydraulic connectivity to other structures, and to determine its hydraulic properties on a relatively large scale.

Long-term interference pumping tests in open holes are aimed at providing information on the hydraulic properties of the bedrock within a large portion of the investigation area. The pumping test is then carried out in a strategically situated open borehole, i.e. without packer seals. The resultant groundwater lowering is monitored as before between packers in adjoining boreholes. The average permeability of the bedrock in the area can be determined from these tests.

Interference tests can be combined with tracer tests, whereby one or more tracers are injected in one or several of the observation points (continuously or in the form of pulses). The concentration of the tracer in the pump hole is then recorded during the course of pumping, along with where influxes are taking place in the pump hole, if possible.

In order for it to be meaningful to conduct interference tests and tracer tests, the concerned rock volume must be free from other hydraulically disturbing activities so the tests can be interpreted correctly. This is true for all hydraulic tests, but particularly for these long-duration tests, since they also encompass a large investigation volume, imposing extra stringent demands on planning and coordination.

In-situ measurement of groundwater flow

There are also methods for *in-situ measurement of groundwater flow*, which can be used for calibration and/or verification of numerical model calculations of groundwater flow. The dilution method entails measuring the dilution of a tracer injected into a sealed-off borehole section. Provided the method is performed under undisturbed conditions, the dilution is determined by the groundwater flowing through the section, from which the flow rate out into the rock can also be estimated. Different applications exist for the method, where e.g. tests in short sections provide information on individual water-bearing zones, even minor ones.

Hydraulic investigations in soil

The hydraulic properties of soil strata (permeability etc) are estimated indirectly from knowledge of soil minerals or determined by analysis of samples, infiltration tests and pumping tests.

Monitoring of groundwater table and groundwater pressure

Monitoring of the groundwater table in open boreholes *and groundwater pressure* in packered borehole sections should be initiated as soon as possible after the borehole investigations have been carried out. The information is used to determine boundary conditions and for calibrating groundwater models (see section 5.1). During hydraulic tests, it is possible to determine the groundwater pressure in the tested sections more or less accurately. Depending on the measurement system, this is done either by determining the relative pressure distribution along the borehole or by measuring absolute pressures.

The monitoring system can also be used for indication of hydraulic disturbances, e.g. in conjunction with the drilling of new holes. The information can then be used together with data from the actual drilling to identify water-bearing zones, i.e. monitoring can be utilized as a simple form of interference test.

If saline groundwater is present, which is relatively common at great depth, this must be taken into account in the execution of most hydraulic tests, but particularly in connection with pressure determination, pumping tests and flow logging without packers. The saline groundwater may cause the water column in the borehole to have a different density from that of the groundwater in the surrounding rock. It is especially in conjunction with tests that include pumping from an open hole that possible movement of the interface between fresh and saline groundwater must be taken into consideration. It is essential to take into account the presence of saline groundwater in pressure measurement as well.

Besides monitoring of the groundwater table and groundwater pressure in boreholes, *monitoring of meteorological and hydrological parameters* is also done. Data on precipitation, temperature, air pressure, snow depth, drainage basins, stream flows are acquired either from recordings in the vicinity or by measurement of these parameters.

Mapping of the regional flow pattern

The regional flow pattern is calculated essentially from topography, historic shoreline displacement, interpreted groundwater recharge and interpreted hydraulic properties on a regional scale. Data are also collected to determine whether the calculated flow patterns are reasonable. Significant recharge and discharge areas are mapped on a regional

Table 4-3. Compilation of hydrogeological parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during FS	ISI	CSI	DC
Deterministically modelled fracture zones	Geometry – regional and local fracture zones (see geology table)	x	x	x	x
	Deterministic or statistical distribution of transmissivity or hydraulic conductivity		x	x	x
	Storage coefficient		(x)	x	x
Stochastically modelled fracture zones, fractures and rock mass	Geometry – rock volumes with similar hydraulic properties	(x)	x	x	x
	Statistical description of the spatial distribution and geometric properties of the fracture zones. Statistical distributions of transmissivity		x	x	x
	Statistical distributions of hydraulic conductivity		x	x	x
	Statistical distributions of specific storage and storage coefficient		(x)	x	x
Soil strata	Geometry – soil volumes with similar hydraulic properties		x	x	
	Hydraulic conductivity		(x)	x	
	Specific storage		(x)	x	
Groundwater's hydraulic properties	Density, viscosity and compressibility		x	x	x
	Salinity		x	x	x
	Temperature		x	x	
Boundary conditions and supporting data	Meteorological and hydrological data	x	x	x	(x)
	Recharge/discharge areas		x	x	x
	Pressure or head in borehole sections and surface watercourses.		x	x	x
	Groundwater flow through borehole		(x)	x	x
	Regional boundary conditions, historic and future development		x	x	(x)

scale. Chemical water sampling and hydraulic tests in one or a few deep boreholes situated outside the priority site may be carried out. The number and locations of holes are determined by the results of the initial regional flow modelling.

The hydrogeological parameters to be determined during the site investigation phase are summarized in Table 4-3.

4.3.5 Hydrogeochemical investigations

The purpose of the hydrochemical investigations is to investigate the chemical composition of the groundwater. The chemical composition of the rock (mainly rock types and fracture-filling minerals) is determined for the most part in the geology programme. Sampling and analysis will be carried out in accordance with well-established procedures devised for the purpose by SKB /SKB, 1998/. The characterization is based above all on data from deep cored boreholes, percussion boreholes, existing wells and springs, and to some extent surface water as well. The activities are focused on the priority site, but water samples in boreholes outside of this site are also used to obtain a picture of the large-scale distribution (regional trends) of groundwater composition.

The hydrogeochemical characterization is highly dependent on the execution of samplings at the right place, at the right times, and in the right way. As mentioned previously, sampling is very sensitive to disturbances. Water samples may be mixed with alien water, even though sampling as such has been performed in a correct and well-controlled fashion. This may be due to the fact that flushing water has penetrated into the rock for such a long time that the sampling procedure has not been able to compensate for this. It may also be due to the fact that a borehole has caused a short circuit between different groundwater-bearing units. If this is the case, the water sample may consist of a non-representative mixed water. Incorrect water samples can be caused by poor sampling methodology, incorrect execution or improper handling. All of these problem areas must be managed and mastered.

The main purpose of *hydrogeochemical sampling in conjunction with drilling* is to take water samples before the site or the borehole has been subjected to prolonged disturbance. In the case of water sampling in conjunction with drilling, a relatively large quantity of water samples can be taken with a good distribution over the investigated site. However, only a limited number of chemical parameters can be determined on these water samples, mainly because the sampling methodology does not permit reliable analysis of certain parameters. A more advanced sampling programme must therefore be carried out, known as complete chemical characterization, using SKB's mobile sampling and analysis system (see below).

Hydrochemical logging is a relatively simple and fast method for taking water samples along a whole borehole. The method entails lowering a hose slowly down along the borehole, whereby water constantly flows in through the mouth of the hose. The water column that is then built up inside the hose corresponds to the water column out in the borehole. Since the hose has joints at regular intervals, for example every 50 metres, and fitted with non-return valves, the water is retained inside the sealed-off hose sections when the hose is lifted up to the surface again. The hose sections are emptied and the samples can be analyzed. This method provides a relatively fast means for type classification, but an important limitation is that only water from the open borehole can be sampled, and this water does not necessarily represent the water inside the rock at the same level.

The *complete hydrochemical characterization* that is carried out with SKB's mobile sampling and analysis system (Figure 4-5) is more comprehensive and thereby more time-consuming. It is therefore carried out in a limited number of boreholes, which are selected strategically over the entire site so that the chemical properties of the groundwater in water-bearing fracture zones, individual fractures and rock mass can be determined with good certainty. This sampling programme is focused on rock units with a permeability in the range 10^{-6}–10^{-8} m/s, which means it mainly samples groundwater from individual fractures or local minor fracture zones. This water is judged to be the water that will come into contact with the deep repository's engineered barriers (bentonite and canister). Sampling is done from sealed-off borehole sections, and Eh and pH are measured with electrodes in the sampling section. In-situ measurement of these parameters is done to exclude the possibility of changes caused by the fact that the water may be contaminated during its transport up to the ground surface by e.g. oxygen or be changed by the fall in pressure. Oxygen can diffuse in through pipes and hoses, especially since the low water flows (often less than 0.1 l/minute) result in relatively long

Figure 4-5. *SKB's mobile hydrochemical sampling and analysis system.*

residence times. The pumped-up water is analyzed both in the mobile field laboratory and at external water laboratories. Pressurized water samples are also taken directly down at the sampling section, partly to analyze the gases dissolved in the water, and partly to be able to study the water's bacteria content.

Water from more permeable portions of the boreholes can be sampled using simpler methods in conjunction with hydraulic pumping tests without appreciably compromising the quality of the water samples. This is mainly due to the fact that the pump capacity is great and the water's residence time in hoses or pipes is thereby very short. The sample water can then be allowed to flow through a measuring cell for recording of Eh and pH before it comes into contact with the oxygen in the air. This sampling is expected to result in virtually the equivalent quality as the in-situ measurement at low pump capacity. Usually, the same chemical analyses are performed on these samples as on those mentioned previously. The difference lies in the fact that no pressurized samples are taken down at the sampling section, so neither gas or bacteria content can be determined.

Sampling of surface water and superficial groundwater (springs, dug wells) is also carried out to complement the hydrogeochemical characterization at depth in the bedrock. These samplings and analyses are relatively uncomplicated. The same applies to groundwater characterization from own investigation holes of a simpler type.

A number of sampling points from surface water, wells, and shallow and deeper investigation boreholes are selected for regular follow-up sampling, called *hydrochemical monitoring*. The purpose of this monitoring is to identify any relatively short-term chemical changes (during the site investigation phase), but above all to initiate a long-term monitoring, which is particularly important for the site that will be selected for detailed characterization. The sampling points are chosen strategically to represent both superficial and deep groundwater within different groundwater reservoirs. Hydrochemical monitoring is coordinated with hydrogeological monitoring.

The hydrochemical parameters to be determined during the site investigation phase are summarized in Table 4-4.

Table 4-4. Compilation of hydrogeochemical parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during FS	ISI	CSI	DC
Variables	pH, Eh		x	x	x
Main components	TDS (sum of main components:) Na, K, Ca, Mg, HCO_3, SO_4, Cl, Si		x	x	x
Trace substances	Fe, Mn, U, Th, Ra, Al, Li, Cs, Sr, Ba, HS, I, Br, F, NO_3, NO_2, NH_4, HPO_4, REE, Cu, Zr		x	x	x
Dissolved gases	N_2, H_2, CO_2, CH_4, Ar, He, C_xH_x, O_2		x	x	x
Stable isotopes	^2H in H_2O, ^{18}O in H_2O and SO_4, ^{13}C in DIC and DOC,^{34}S in SO_4 and HS, $^{87}Sr/^{86}Sr$, ^3He, ^4He, (Xe isotopes, Kr isotopes)		x	x	x
Radioactive isotopes	T, ^{14}C in DIC and DOC, $^{234}U/^{238}U$, ^{36}Cl, ^{222}Rn		x	x	x
Others	DOC (Dissolved organic matter), humic acids, fulvic acids, colloids, bacteria		x	x	x
Fracture-filling minerals	$\delta^{18}O$ $\delta^{13}C$,$^{86}Sr/^{87}Sr$, $^{235}U/^{238}U$, morphology in calcite and iron oxides			x	x

4.3.6 Rock-mechanical investigations

The purpose of rock-mechanical investigations is firstly to determine the state of stress in the rock mass, and secondly to determine the deformation and strength properties of the intact rock and natural fractures contained in it.

Rock stresses will be measured by means of two methods: *overcoring* and *hydraulic fracturing*. Owing to uncertainties in both of these methods, they will be used in combination wherever possible. The measurements will be carried out both within a range of depths, e.g. 100–800 metres, in order to obtain trends with depth, and within probable repository levels in order to obtain spatial distribution. The geological-structural conditions that are identified will influence the scope of the measurements.

Overcoring is carried out in conjunction with drilling, whereby a number of strain gauges are installed in different directions in a smaller pilot hole at the desired measurement depth. The manner in which the strains in these gauges change when a cylindrical core of rock around the pilot hole is overcored and freed from the rock's stress field is then measured, see Figure 4-6. The measurements are normally performed for at least four points per level to enable a mean value of the stress tensor to be calculated. The method permits three-dimensional calculation of the state of stress from measured strains and presents the direction and size of the three orthogonal principal stresses. The method presumes that the rock has an elastic response to overcoring. It is relatively time-consuming, but such measurements will probably be performed in some boreholes during both the initial and the complete site investigation.

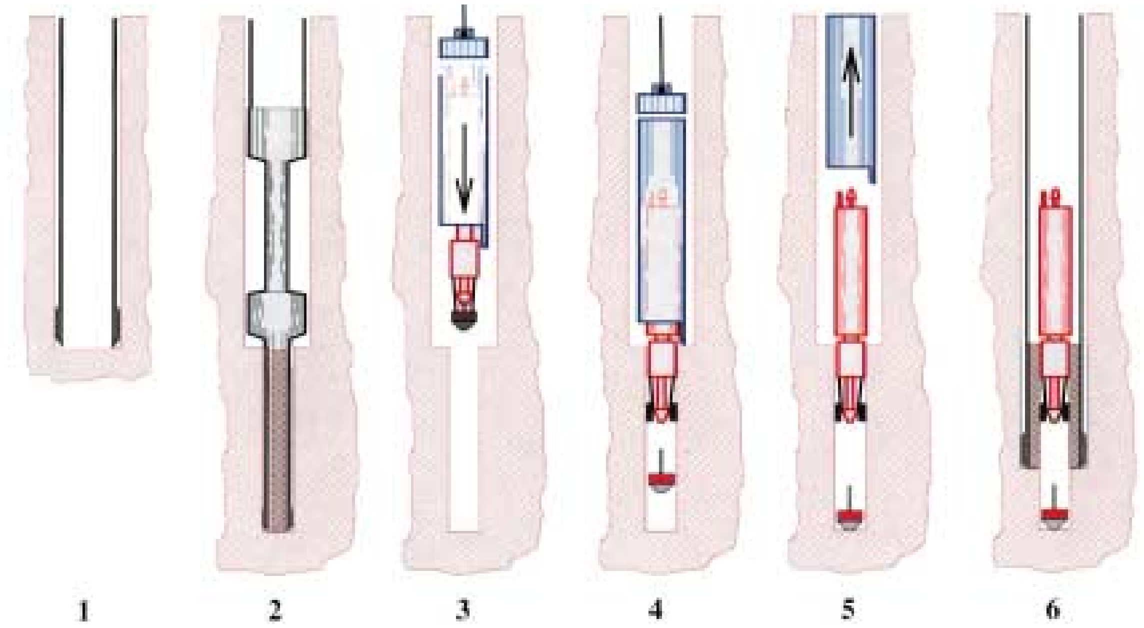


Figure 4-6. *Sequence showing the execution of a stress measurement by means of the overcoring method. At the chosen borehole depth (1) a short pilot hole is drilled (2) in which the measuring probe with wire strain gauge is fitted (3–5). Overcoring (6) releases the rock stresses, which are recorded by the measuring probe.*

Hydraulic fracturing involves enclosing a borehole section and then splitting the rock with water pressure. Sealing packers can then be used to determine the direction of the induced fracture. In the case of a vertical hole drilled in homogeneous rock, the rock normally fractures parallel to the maximum horizontal stress, i.e. along the borehole. By measuring the water pressure needed to keep the fracture open, it is possible to calculate the minimum stress in the plane perpendicular to the borehole – normally the horizontal plane, since the method is usually used in vertical boreholes. The maximum stress is calculated on the basis of theoretical assumptions. The vertical stress cannot be measured in this way, but can in many cases be assumed to correspond to the vertical rock load. The method is slightly faster to use than overcoring and can be carried out in existing boreholes. It therefore permits a larger number of measurement points. Since water is injected in this method, however, measurements must await the conclusion of all sensitive hydraulic tests.

The two methods are usually combined in different ways, either in the same borehole or in different boreholes. Provided that hydraulic fracturing can be used, it will be possible to perform more measurements with this method. The quantity cannot be decided in advance, but it can be assumed that hydraulic fracturing for the whole site investigation phase will be performed in about 4–7 boreholes, while overcoring will be limited to 2–4 boreholes.

One variant of hydraulic fracturing is called "Hydraulic Tests in Pre-existing Fractures" (HTPF). As the name implies, this method entails using water pressure to measure the pressures prevailing over existing open fractures. However, the method presumes the presence of at least three fracture groups at a large angle to each other within a limited range of depths. Experience with this method is limited, but it is potentially applicable under conditions where hydraulic fracturing is not applicable.

High rock stresses, particularly highly anisotropic ones, can be indicated by the occurrence of core discing, by which is meant that the drill core ruptures into discs. The phenomenon is a good indicator, but not adequate to determine with certainty whether unsuitable stress conditions and strength properties prevail.

The stresses in the rock are greatly affected by the occurrence of fracture zones and fractures, near which the stresses can vary in both size and direction. This needs to be taken into account when locating measurement points and evaluating the results.

The measurement results are also affected by the measurement scale, which is mainly determined by the measurement method employed. The results of overcoring represent a smaller rock volume (on the order of one borehole diameter) than the results of hydraulic fracturing.

Other rock-mechanical parameters that are studied during site characterization have to do with the mechanical properties of the intact rock and of individual fractures. These parameters are determined both by mapping and *laboratory analyses of rock samples*, above all drill cores, and with the support of generic knowledge concerning these parameters as regards their relationship and dependence on rock type.

The rock-mechanical parameters to be determined during the site investigation phase are summarized in Table 4-5.

4.3.7 Determination of the thermal properties of the rock

Data on the thermal conductivity, heat capacity and coefficient of thermal expansion of the rock are determined above all from known data for the relevant rock types. The information is supplemented by direct measurements on drill cores in the laboratory. Only the temperature of the rock is measured in the field, as a part of the geophysical logging programme.

The thermal parameters to be determined during the site investigation phase are summarized in Table 4-6.

4.3.8 Determination of the transport properties of the rock

The transport properties of the rock are above all dependent on the geochemical and hydraulic properties of the bedrock, the chemical properties of the groundwater and the physical properties of the rock matrix, such as matrix porosity and matrix diffusivity (Figure 4-7).

The rock's retention capacity (transport resistance) for different nuclides is very difficult to determine site-specifically by means of field measurements, in part due to the fact that sorption is very strong, resulting in very slow transport and thereby a long transit time. However, an important portion of the transport resistance is determined by the distribution of the groundwater flow in the rock, see /SKB, 1999a/. This portion can be statistically well determined during the site investigation as well.

Laboratory tests on rock samples provide valuable information on the transport properties of the rock matrix. Most of the transport parameters that are used for various analyses and calculations during the site investigation phase are, however, based on SKB's general knowledge of conditions in the crystalline bedrock and are determined by earlier tests on

Table 4-5. Compilation of rock-mechanical parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during			
		FS	ISI	CSI	DC
Fracture zones	Geometry, see geology table		x	x	x
Mechanical properties of fractures	Deformation properties in normal direction			x	x
	Deformation properties in shear direction			x	x
	Shear strength			x	x
Mechanical properties of intact rock	Modulus of elasticity (Young's modulus)		x	x	x
	Poisson's ratio (n)		x	x	x
	Compressive strength		x	x	x
	Tensile strength		x	x	x
	Indentation index, RDI, wear index			x	x
	Blastability				x
Mechanical properties of rock mass	Modulus of elasticity (Young's modulus)			x	x
	Poisson's ratio (n)			x	x
	Rock classification		x	x	x
	Dynamic propagation velocity, compression wave		x	x	x
	Dynamic propagation velocity, shear wave			x	x
	Strength			x	x
Density and thermal properties	Density		x	x	x
	Coefficient of thermal expansion		x	x	x
Boundary conditions and supporting data	In-situ stresses, magnitude and directions		x	x	x
	Observed deformations and seismic activity	x	x		

Table 4-6. Compilation of thermal parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during			
		FS	ISI	CSI	DC
Thermal properties of the rock	Thermal conductivity – rock		x	x	x
	Heat capacity – rock		x	x	x
Temperatures	Temperature in rock and groundwater		x	x	
	Thermal boundary conditions/gradient			x	

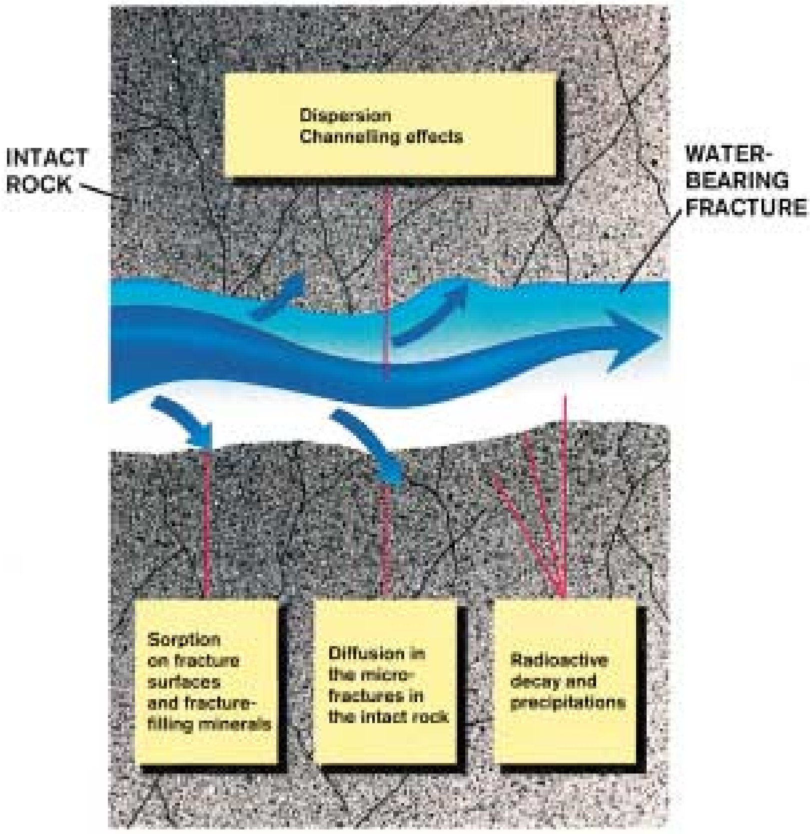


Figure 4-7. *Illustration of the mechanisms that influence the transport of radionuclides in crystalline rock.*

various rock materials, in the field and in the laboratory. In principle, the mineral composition of the rock is important for the sorption properties, but the mineral composition does not vary so much. The sorption properties are above all dependent on the chemical composition of the groundwater, so sorption data are mainly determined from the determination of groundwater composition. The laboratory tests include determination of matrix diffusivity, matrix porosity and sorption coefficients for a selection of substances. Estimates of maximum penetration depth are made with the aid of e.g. fracture-filling mineral analyses and special porosity measurements. The measurements are made on a selection of site-specific rock material and fracture surfaces, where the coupling to SKB's earlier investigations is important.

Tracer tests in the field are used in the site investigation to verify that the transport parameters determined in laboratory measurements, as well as those interpreted from hydraulic and geological information, are reasonable. In practice, tracer tests can only be done with non-sorbing or weakly sorbing substances. The tracer tests can provide some idea of transport resistance, flow porosity, transport pathways (connectivity) and dispersion. Since traditional cross-hole tracer tests between boreholes are relatively time-consuming, single-hole methods will also probably be used. This enables more measurements to be made and provides a more reliable basis for determination of site-specific transport parameters. However, the majority of the tracer tests will presumably be carried out during the detailed characterization phase.

The transport parameters to be determined during the site investigation phase are summarized in Table 4-7.

Table 4-7. Compilation of transport parameters that will be determined in various phases. Initial site investigation (ISI) and complete site investigation (CSI) belong to the site investigation phase and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during			
		FS	ISI	CSI	DC
Properties on deposition hole scale	Groundwater chemistry		x	x	x
	Groundwater composition		(x)	x	x
	Fracture aperture, geometry			(x)	x
Properties along flow paths	Flow paths*		(x)	x	x
	Transport resistance along flow paths*		(x)	x	x
	Dispersivity*			x	x
	Flow porosity*			x	x
Properties in rock	Sorption data (K_d)			x	x
	Matrix diffusivity			x	x
	Matrix porosity			x	x
	Max. penetration depth			x	x
	Groundwater chemistry			x	x
Supporting data	Tracer tests			x	x
	Chemical analysis of fracture-filling material			x	x
	Chemical analysis of wall rock				
	Groundwater chemistry			x	x

* Calculated by evaluation of other data and/or modelling.

4.4 Further development of investigation methods

A fundamental principle for investigation methods and measuring instruments over the years has been to give preference to using existing and commercially available technology. SKB's often very special needs for information from great depth have, however, compelled the company to conduct extensive method and instrument development of its own as well. SKB's international network, e.g. in the form of exchange of information and knowledge as well as joint development projects, is another source of method knowledge. A long list could be made of methods which SKB has developed on its own, or contributed significantly to the development or refinement of. Development efforts are still being pursued and new ones will be initiated in the future as well.

The investigation methods presented in this programme (see appendix) are to be regarded as available methods that may be used in the future. Which methods will actually be employed is a question for the site-specific programmes and the detailed plans for execution of the site investigations. It is essential that the methods used are tried-and-tested and documented. The use of these methods will also be governed by method descriptions (see Chapter 6). This is not to say that new methods and technology will not be developed, but it is necessary here to be extra observant of the fact that the practical usefulness of new methods may not yet be fully verified. With an appropriate quality system, however, this should also be able to be managed with good control and traceability.

With the investigation programme as a basis, SKB conducts regular cross-checks of the knowledge situation and availability of resources within the area of investigation methods and instruments. These cross-checks provide the impetus for development initiatives as well as for further or new development and prioritization of methods that can be used to determine the more critical parameters in the safety assessment. The Äspö HRL provides particularly valuable experience when it comes to trying out new measurement methods for e.g. the transport properties of the rock. A few examples of the development of methods and instruments currently being pursued by SKB are given below.

With the assistance of Uppsala University, the seismic reflection method has been further developed for practical use in site investigations. Both measurement methodology and analysis methodology have been improved, the latter by e.g. utilizing the modelling tool RVS (Rock Visualization System) for interpretation of the three-dimensional extent of structures. Method tests conducted previously in deep boreholes at Laxemar are now being supplemented by VSP (Vertical Seismic Profiling). The purpose is to optimize the application of this method and refine the co-interpretation of the two seismic methods. Such a "seismic survey package" is included in the planning for the initial site investigations.

Development of RVS as a computer aid for three-dimensional modelling and visualization of rock continues. Methodology is being developed for geometric modelling and presentation of interpreted discipline-specific properties for modelled geometric elements. An essential component in this work is management of model versions and documentation of interpretations.

The borehole radar that was developed within the framework of the Stripa Project is being replaced by a new radar method based on modern technology.

A thorough review of rock stress methods is currently being conducted to obtain further knowledge on the measurement accuracy of the different methods and their applicability for site investigations. In this connection, measurements are being performed with overcoring and hydraulic fracturing in the cored boreholes currently being drilled in SKB's instrument storehouse in Oskarshamn.

A new method for water sampling and hydraulic testing during drilling is also being tested in the same borehole. The new method is designed for drilling with the wireline technique, which enables the equipment to be raised and lowered more rapidly. The borehole in the instrument storehouse will later be of great use both for testing and calibration of equipment and for training of measurement personnel.

A new length calibration method for correct positioning of measurement points along a borehole will be tested after the borehole in Oskarshamn has been completed.

Together with Posiva, SKB is carrying out a measurement programme for testing and to some extent further development of the differential flow logging method. This is being done in the deepest borehole at Laxemar, where it is of particular interest to investigate the method's ability to handle the high salinities that occur at great depth. SKB's cooperation with Posiva also includes testing their new water sampler in the same borehole. The results of this test have already been of use for the new water sampling system that is being developed.

Some method development for determination of transport properties is taking place in connection with TRUE (Tracer Retention Understanding Experiments) at the Äspö HRL, for example with regard to alternative methods for determination of matrix diffusion and development of single-hole methods for tracer tests. At KTH, a project is being conducted aimed at investigating whether it is possible to determine matrix diffusivity with the aid of data from resistivity logging.

5 Evaluation of the site-specific information

Based on the measured site-specific information, the principal activity *investigations* prepares geoscientific models of the site. *Design* uses these models to prepare a site-specific facility description with facility layout and assesses the consequences of the civil engineering work. The *safety assessment* evaluates long-term safety on the basis of specified site models and repository layout. Knowledge of the site emerges step-by-step, which is why the various analyses of the site must also be performed in steps. Results of early analyses may be used to guide the thrust of the continued investigation activities in later steps. The various principal activities must therefore interact.

5.1 Geoscientific modelling

When the site investigations are finished on a site, the activity *investigations* shall have:

- presented the necessary data on the site for a site-adapted layout of the deep repository and assessment of the deep repository's long-term radiological safety to be carried out,
- achieved fundamental geoscientific understanding, i.e. have analyzed the reliability and assessed the reasonableness of the assumptions made with respect to the current states of the site and naturally ongoing processes,
- identified objects that may require special environmental considerations during construction and operation of the deep repository.

The investigations furnish primary data (measurement values and directly calculated values), which are collected in a database. In order to be able to make use of the collected (measured) information for design and safety assessment, and to judge the reliability of the information, it must be interpreted and presented in a geoscientific model, Figure 5-1. The geoscientific model consists of a description of the geometry and various properties of the site: a site description.

The geoscientific model of a site is prepared and updated stepwise during the course of the site investigations. Model versions are prepared as new information becomes available. In order to be able to maintain traceability and consistency between different disciplines, strict version management is applied (cf. Chapter 6). It must be clearly evident which measurement data underlie a given model version. When the activities design or safety assessment use site-specific information, the relevant model version must always be specified. Sections 5.2 and 5.3 describe how the different model versions are used in different stages of the design and safety assessment work. Note, however, that the number of model versions may be modified. Either fewer or more model versions may be developed, depending on the local conditions and how easy it is to interpret the studied site. This in turn influences the interplay with other actors. To handle the uncertainty in the interpretation of data, especially in the initial stages, alternative descriptions may also be formulated.

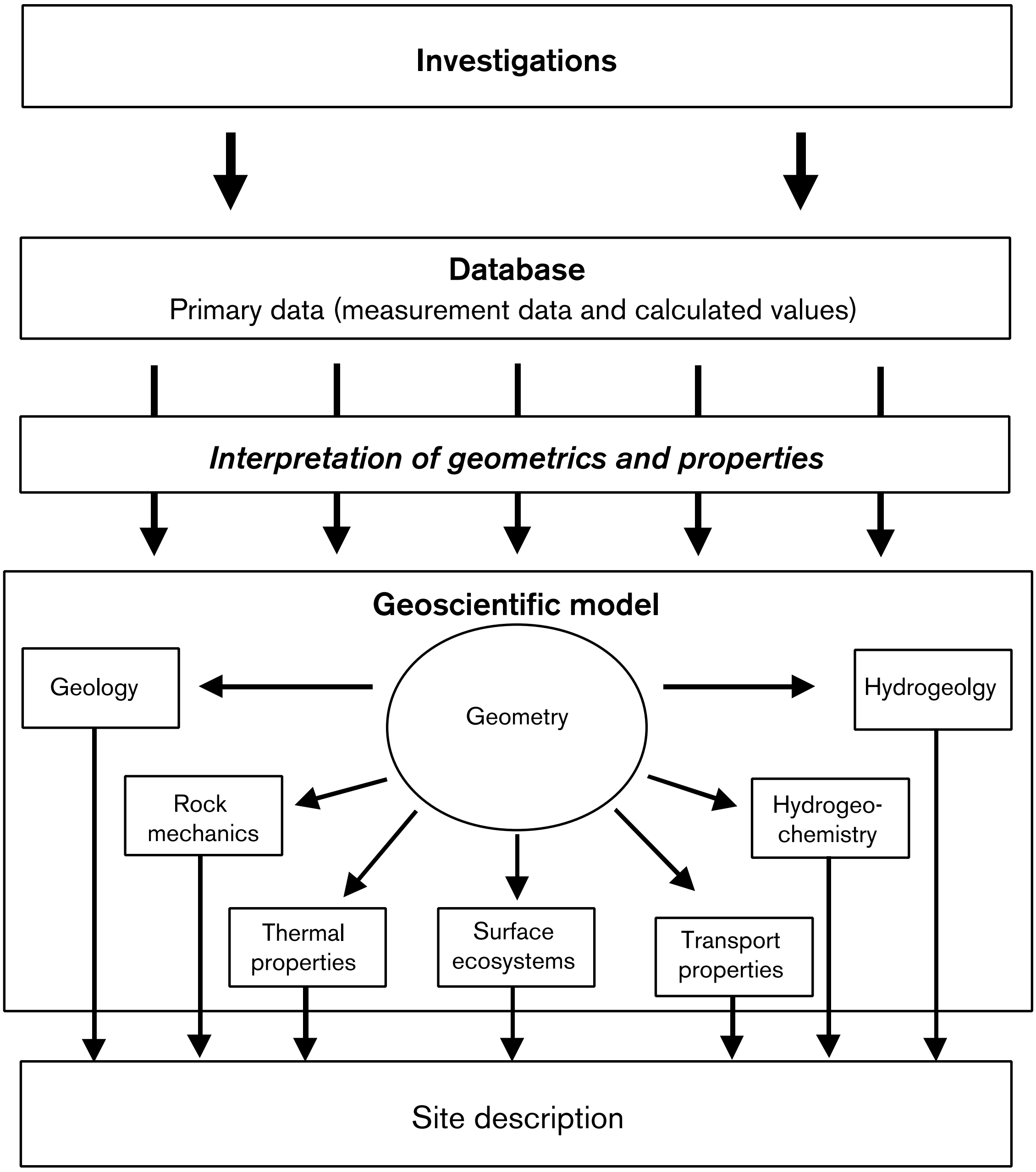


Figure 5-1. *The primary data from the investigations are collected in a database, which is interpreted and presented in a geoscientific model, which consists of a description of the geometry and various properties of the site.*

5.1.1 Geoscientific models

The results of completed measurements must be analyzed and interpreted to enable a description of the site to be written that can be used for design and safety assessment. Based on the investigation results, a three-dimensional geoscientific model (depiction) of the rock is built. The model consists of different geometric units in soil and bedrock, which are essentially determined by the geometry of fracture zones and the distribution of Quaternary deposits and rock types. The following are described for each geometric unit: the *geological* conditions; the *mechanical*, *thermal*, *hydraulic* and *chemical* properties; and properties of importance for *radionuclide transport* in the rock. In addition, the *surface ecosystems* are described.

The properties that need to be included in the geoscientific model are determined by the need of the design activity to produce a facility description, the need of the safety assessment to study the long-range evolution of the repository, and the need to achieve and demonstrate geoscientific understanding. The processes that control repository evolution determine which properties of the rock need to be described in the geoscientific model. For example, in order to describe the long-term thermal evolution of the repository, descriptions of the current temperature and thermal conductivity of the rock are required. The transport properties that need to be described in the geoscientific model are controlled by the mathematical model that is used to calculate radionuclide transport in the safety assessment.

The level of ambition for the description is based on the need that has emerged from previous studies. The structure of the geoscientific model will be based on the development and application that has been done at the Äspö HRL and in SR 97 /Olsson et al, 1994; Rhén et al, 1997b; SKB, 1999a/. Different properties that should be included in the description are identified and described in the "Parameter report" /Andersson et al, 1996/ and in the report on requirements and criteria /Andersson et al, 2000/, see also section 4.1.1 and the tables in section 4.3.

The rock is investigated with boreholes, while the endeavour in the geoscientific model is to provide a full description in three dimensions. The measurement results therefore need to be interpolated and extrapolated to include the entire rock volume. This can be done using different conceptual models describing the structure of the rock. This is particularly true of the hydrogeological description. In these cases, several alternative descriptions should be produced. In this way the safety assessment can better analyze the implications of different assumptions and uncertainties.

The geoscientific description is mainly developed to permit forecasts of the future evolution of the repository with the aid of mathematical modelling tools in the safety assessment. Geoscientific modelling and design also need to use mathematical calculation models. The description of the rock is complicated by the fact that several of its properties (parameters), e.g. permeability, cannot be measured directly. Measurements to determine these parameters instead entail that the rock is subjected to a disturbance, e.g. a pumping test, whereby the consequences of the disturbance are observed. To determine the model's parameter values, the measurement is simulated by predicting the consequences of the measurement with the aid of a mathematical model. The parameter values are adjusted so that the calculated consequences agree with the observations. Calculations with mathematical models are also used to simulate the historical evolution of the site. Such so-called paleohydrogeological analysis may be used to shed light on whether the description of the various properties of the site in terms of different disciplines (mainly hydrogeology and hydrogeochemistry) appears reasonable and thereby advances the geoscientific understanding of the site.

The distinction between the calculations that are carried out within the framework of geoscientific modelling and the modelling that is done within the principal activities of design and safety assessment is not clear-cut and should not be perceived as being too strict. Most of the technical calculation work will probably be carried out within the framework of design and safety assessment. A far-reaching integration of the modelling work is needed, see further section 5.3.1.

A *local site model* is devised for each site to describe conditions within the area in which the repository is expected to be located, including access tunnels and the immediate environs. The local site model is expected to cover a geographic area of about 5–10 km^2.

In addition to the local models, *regional site models* are devised to set boundary conditions and to put the local models in their context. The geographic scope of the regional site models is dependent on local conditions and is governed by the need to achieve an understanding of the conditions and processes that determine the conditions on the site. Generally speaking, the scope must be large enough to provide an understanding of the model's boundary conditions.

A brief account of the scope of the geoscientific description is provided in the following section. A considerably more detailed description will be included in the coming discipline-specific programmes.

Geological and geometric description

The basis for an integrated geoscientific characterization is a geometric representation of the topography, deformation zones, lithological boundaries, rock units, soil strata and watercourses on the investigated site and a description of these for the different disciplines. It is necessary that a common geometric model be used for all disciplines. The geometric bedrock model will be based mainly on geological information, but information from the databases for the other disciplines is also included in the body of underlying data, see Figure 5-1. SKB's computer program for visualization, the Rock Visualization System (RVS), Figure 5-2, will be the central tool in the geometric model, and a methodology for how to use it is under development.

Each unit in the geometric model is described with geoscientific properties that have been interpreted from the primary measurement values in the database. According to the model structure which SKB will use, the geological bedrock model consists of a structure part and a lithological part. The deformation zones and fractures in the bedrock are described in the structure part. The distribution and composition of the rock types are described in the lithological part.

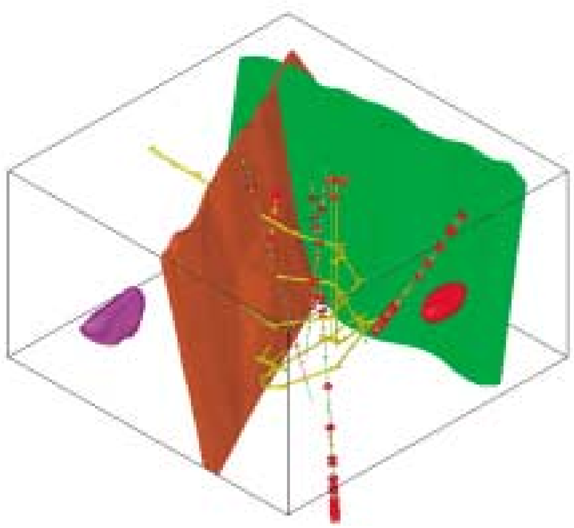


Figure 5-2. *Example of visualization of borehole, fracture zones and tunnels with RVS.*

In order to obtain a consistent terminology that can be understood by the representatives of different disciplines, SKB uses the collective term "fracture zones" to designate all types of deformation zones where the deformation has been of a brittle character, and "plastic shear zones" where the deformation has been of a plastic character. SKB has further chosen to classify fracture zones according to length (size) and to use the designations "regional fracture zones", "local major fracture zones", "local minor fracture zones" and "fractures" (see Table 5-1).

Due to the often complex structure and geometry of the fracture zones, the borderlines for the classification in Table 5-1 are somewhat fluid, depending on the scale or the purpose of the investigation. The location and extent (size) of regional and local major fracture zones can often be determined deterministically. By this is mean that the locations of the fracture zones can be established with good accuracy during the site investigations. For local minor fracture zones and fractures, this is not possible in the entire rock mass that describes the conditions for a deep repository and its environs. Instead, statistical descriptions of the number (density), orientation and size of the zones or the fractures are used. The stipulated level of ambition provides guidance on how much data are required. Many local minor fracture zones, which are only described statistically during the site investigations, will be investigated more thoroughly in subsequent detailed characterization so that they can also be described more or less deterministically within parts of the repository volume. It should be observed that the classification does not necessarily entail any evaluation of the properties or importance of the fractures or fracture zones for the deep repository. The specific properties of the zones are dealt with in the model description for the relevant discipline.

Description of the rock dominates the geological model, but it also includes description of the soil strata. The description of *Quaternary deposits* provides a basis for modelling of the surface hydrology and for the analysis of the surface ecosystems. This information is in turn used for the safety assessment's biosphere modelling and as a basis for the environmental impact statement (EIS). The description of an area's topography is also included in the geological model. As a basis for the understanding of the geological conditions, a description of the area's geological evolution in a historical perspective is also prepared.

Table 5-1. Classification and naming of the bedrock's fracture zones and fractures (brittle structures), and ambition level for geometric description during site investigation (length and width measurements are approximate).

Name	Length	Width	Ambition for geometrical 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

Rock-mechanical description

The rock-mechanical model describes the distribution of the rock's mechanical properties and state of stress on different scales. The geometric description gives rock stresses, strength and deformation properties for the intact rock and the rock mass, as well as geometry, strength and deformation properties for the fracture zones and major fractures in the rock. The information is presented in such a manner that different calculation models can be used to analyze mechanical questions on different scales.

Thermal description

The thermal description mainly identifies parameters of importance for transport of heat (thermal conductivity and heat capacity) and ambient temperature (initial temperature, surface temperature and geothermal gradient). The properties are determined primarily from the lithological model.

Hydrogeological description

The hydrogeological description includes hydraulic properties for the different rock domains (fracture zones and rock mass), the groundwater conditions on the site and the processes that govern the natural flow of the groundwater. The hydrogeological model mainly gives the permeability of fracture zones and fractures, flow porosity and storage coefficient, the distribution of density and viscosity in the groundwater, and hydrogeological data for the surface ecosystems. Measured hydraulic heads and interpreted locations of recharge and discharge areas are indicated. The latter information can be used to set boundary conditions or otherwise assess the reasonableness of the model.

There are different conceptual models for describing the spatial variation of the hydraulic properties of the rock. The two foremost ones are the discrete fracture network model and the continuum model. In the first model concept, the location, size, orientation and hydraulic properties of each fracture are defined explicitly. In the second, the resolution is coarser and the properties vary continuously in the rock volume. Which model is most appropriate depends partly on which scale is to be studied. In the hydrogeological characterization, parameters should be chosen to meet the needs of the different model concepts to as high a degree as possible. SKB plans to describe the properties of the rock both deterministically and stochastically. In the latter case, the models are normally called stochastic continuum and stochastic discrete fracture network.

Hydrogeochemical description

The hydrogeochemical description includes the groundwater's (chemical) composition and distribution in the rock. The description is based primarily on measurements of groundwater composition, but also uses the hydrogeological and geological (lithological) model as a basis. The description also serves as a basis for possible simulations of the historical hydrogeochemical evolution of the site.

The composition of the groundwater is affected by surrounding rock types and fracture-filling minerals via precipitation and dissolution processes. Large-scale groundwater movements could in the long term affect the groundwater chemistry on a repository scale by bringing in groundwater of another chemical composition. A key to being able to predict the future evolution of the repository is thereby an understanding of the origin (genesis) of the groundwater, for which knowledge of rock types and fracture-filling minerals is also essential.

Description of the transport properties of the rock

The description of the transport properties of the rock includes the parameters that are needed to calculate transport of solutes and particles with the groundwater, mainly flow-related transport parameters and properties of the rock matrix. It will not be possible to specify transport properties for different pathways through the rock deterministically. A statistical description similar to that done for SR 97 will be used.

Surface ecosystems

The surface ecosystems on the site (forest, lake, meadow, etc) are described in the form of biotopes (flora and fauna), activity (land use, uptake rate), transport of water and particles (meteorological/hydrological data) and hydrogeological properties of the soil strata (permeability, thickness and porosity). The process of postglacial land uplift (crustal upwarping) and shoreline displacement are described. Shoreline displacement is used for erosion models that describe the transport of sediments and the formation of Quaternary deposits. Succession models describe how the vegetation changes with time (forest growth, mire growth and so on). They also provide information on potential resource utilization in the area. System ecology models describe the flow of material through the ecosystems to man and the environment.

This information is needed to describe the turnover, transport pathways and consequences (dose/risk) of radionuclides that escape into the environment, but also to assess the environmental impact of the civil engineering work and adapt proposals for above-ground establishments and their access roads with regard to the environmental conditions. The surface conditions also influence groundwater recharge and the overall groundwater chemistry, even though the groundwater flux at depth is very slow.

5.1.2 Confidence in models and parameters

The level of confidence in the forecasts of the safety assessment is highly dependent on the level of confidence in the models that are devised. This confidence needs to be described in order to evaluate how well-underpinned the safety assessment is. The ambition is to make the models as reliable as possible, but since all models are simplified representations of reality, there will always be discrepancies between the model and reality. The uncertainties contained in the model stem partly from the fact that processes that may have been neglected or simplified and that certain parameters exhibit spatial variability, which can only be handled statistically, and partly from measuring error, measuring accuracy, interpretation methodology, etc. Uncertainties of the latter type are often small, however. Uncertainties must be described and quantified, if possible. It is essential not to be bound by a single model alternative, particularly at an early stage of the characterization. An important means of handling uncertainties and alternative interpretations is to develop alternative descriptions and to analyze the consequences for the different alternatives in the safety assessment. Methodology for this has been tested in SR 97 /SKB, 1999a/.

The reliability of model descriptions is tested by checking the agreement of new sets of measurement data against predictions from current model versions and model alternatives. Certain model alternatives may be discarded and new ones created in this process. One alternative may prove to be more reasonable than others and thereby come to be regarded as the principal model. However, it is important to retain possible alternatives to the principal model and to carry out variation analyses to test the sensitivity of the models. During the final phase of the site investigations, certain investigations may even be carried out specifically for this purpose. On the basis of relevant models, forecasts are then made of the properties of the rock before a new hole is drilled or of how the groundwater reservoir will react to a given hydraulic test. Good agreement between forecast and measurement result is a sign that the models are reasonable in the comparison, while poor agreement indicates the opposite.

Certain parameters can be measured or determined directly. In most cases, however, measurement data provide indirect information that must be interpreted or evaluated with the aid of various types of analysis tools and methods or by means of expert judgements in order that one or more parameters can be determined. In other cases, parameters are determined by measuring and evaluating how the rock reacts to a "disturbance", such as a hydraulic test. Measurements, tests and analyses of soil, rock and water samples are other methods of parameter determination. In some cases it is impossible or very difficult to determine parameters in the field or on laboratory samples. In these cases it may sometimes be more appropriate to determine the parameter during the subsequent detailed characterization. For other parameters, the general knowledge that is available on conditions in similar geological environments may be fully adequate.

Uncertainties shall always be described and discussed in an appropriate fashion in connection with the reporting of results, and not just in the final report but also in all measurement and investigation steps. Such a report is furthermore compatible with the quality assurance requirement of traceability.

Besides describing the uncertainty in the data, it is also essential that the models can credibly explain the current state of the site based on the natural processes that are changing this state. For example, the composition of the groundwater on the site must be reasonable in relation to the lithological composition, fracture mineralogy, groundwater flow and earlier climatic evolution of the site with associated changes in hydrogeological and chemical boundary conditions. Even though such paleohydrogeological arguments cannot be used as formal evidence that models and parameters have been correctly chosen, they are essential in a qualitative chain of evidence for determining the reliability of the models.

It is ultimately the clients, mainly those responsible for the safety assessment and the design work, who can determine when the body of data is adequate and the uncertainties are acceptable. The safety assessment always makes an evaluation of the uncertainty in the underlying data, see e.g. /Andersson, 1999/ and analyzes how these uncertainties influence the forecast of the long-term performance of the repository /SKB, 1999a/. In the layout work, the assessed uncertainties influence how detailed the description of different repository sections can be and how close to known fracture zones the repository sections can be located. Through the planned interactive procedure with progressive information transfer and feedback, it is also possible to steer the investigation activities, at least to some extent.

5.1.3 Model versions during the initial site investigation

Based on available feasibility study data, a general model (*version 0*) is devised that covers the entire candidate area on a regional scale. The model does not contain any new information compared with the feasibility studies, but is built up according to the structure that will be used for the various disciplines during the entire site investigation phase, see section 5.1.1.

Geoscientific models are then revised as the site investigations progress, where in principle each individual investigation stage is accompanied by an updating of these models. Based on model version 0, the first model update (version 1.1) is done using information from the initial surface investigations (mappings and geophysical measurements). The first version's models have no detail and are heavily dependent on generic data. Since the underlying material essentially comes from data obtained in surface investigations, knowledge of the extent (and inclination) of the fracture zones at greater depth is greatly limited. At this point, possible zones are usually assumed to be vertical. In later versions, the generic information is gradually replaced by site-specific information and higher detail resolution and certainty, see Table 5-2.

Once a priority site has been chosen, the local model area is defined and local models begin to be devised. The modelling work is dominated in these initial steps by the geological and geometric description, with the aid of the Rock Visualization System (RVS). The backbone of the other discipline-specific models should also be built at this stage, even if the site-specific information is very limited.

When data have been obtained from the holes drilled during the initial site investigation, model version 1.2 is developed. The geoscientific models are updated as new investigation results are entered in the database. From this phase the modelling work is dominated on the local scale by 3-dimensional representations. From now on the regional models must also be kept updated, however. Up-to-date model versions represented in

Table 5-2. Different versions of the geoscientific models that are developed during the site investigation.

Investigation phase	Basis	Covers	Geoscientific product/model
Initial site investigation	Feasibility studies. Processing of existing data. Field checks.	Part of municipality and regional environs where priority site will be chosen.	General model on regional scale (version 0).
	General surveys from air, surface and short boreholes.	Candidate area (and priority site).	General model (version 1.1). Choice of priority site.
	Investigations from surface and some deep boreholes.	Priority site. (Regional environs).	Preliminary model on local and regional scale (version 1.2).
Complete site investigation	Investigations in many deep boreholes and supplementary ground surveys.	Priority site. Regional environs.	Model on regional and local scale, site description (version 2.1).
	Further deep borehole and supplementary ground surveys.	Priority site. Regional environs.	Revised model on regional and local scale, site description (version 2.2).
	More supplementary surveys.	Priority site. Regional environs.	Finished model on regional and local scale, site description version 2.x).

RVS are expected in this phase to be used effectively in planning of future investigations as well. The geometric and geological models are still the ones to which the greatest efforts are devoted, but at the end of the initial site investigations all discipline-specific models shall exist in updated versions forming a part of the preliminary site model (site description).

Feedback to other analyses

Model versions 0 and 1.1 are included in the initial assessments of the site done in design and safety assessment. All disciplines contribute data for selection of a priority area for further investigations. The assessment made in design of where it is geometrically possible to accommodate the repository, as well as early evaluations of the environmental disturbance caused by the establishment, are important elements in the background material for choosing a priority site.

The preliminary site descriptions are included in the background material needed by the activities *design* and *safety assessment* to make preliminary facility descriptions and safety assessments. These analyses in turn serve as a basis for the planning of the investigation activities during the continued complete site investigation.

5.1.4 Model versions during the complete site investigation

The complete site investigations are carried out in steps. The number of steps cannot be fixed in advance, however, but should be determined by conditions on the site and what is judged to be most rational. The stepwise performance of the complete site investigation does not reflect different information needs or investigation types, but is mainly motivated by the judgement that it is appropriate to carry out one major borehole and measurement campaign, evaluate the results and then, if necessary, supplement the information with more measurements. At least two model versions, *version 2.1* and *versions 2.2*, will be devised during the phase (see Table 5-2). Each version will describe conditions on a regional and local scale, but with a lower degree of detail and greater uncertainties on the regional scale.

Principal rock types are represented deterministically in the geological/geometric model description, i.e. geometric extent and properties are determined for each rock type. Similarly, regional and local major fracture zones are determined deterministically. The occurrence, percentage fraction and properties of subordinate rock types are presented as statistically distributed parameter values. Local minor fracture zones and fractures are described statistically as regards both geometric information and properties. The RVS system will be an essential tool here to an even higher degree than in earlier phases.

Version 2.1 of the models can be complete in the sense that values have been assigned to all model parameters and uncertainties have been estimated. The main changes in later model versions are that parameter values may be revised and the uncertainty interval may diminish.

Analysis of reliability of models

The work of analyzing the reliability of the models is intensified during the complete site investigation. Analysis of uncertainties and development of alternative model concepts is included as a natural part of the interpretation and modelling work. When version 2.1 of the models is available, calculations and analyses are also begun to ascertain whether the site's current condition and assumed transport properties can be explained on the basis of the spatial distribution of groundwater composition, groundwater flow and probable previous change in boundary conditions or other naturally ongoing processes. The results of the analyses are reported in a special document and used as a basis for the safety assessment's safety report.

Feedback

Model version 2.1 comprises the main basis for the design and safety assessment work carried out during the complete site investigation. The revised model versions (2.2 and possibly others) are not expected to feature such fundamental changes that the analysis work has to be completely redone when a new version of the site models is presented. The final facility design and the safety report are of course based on the last model version.

5.1.5 Geoscientific account

Primary data from the investigations are collected in SKB's geoscientific database SICADA. For data sets that for some reason cannot be physically stored in the database, SICADA provides information on where these data are stored. For map-based information in GIS format, a GIS database is established as a complement to SICADA. A separate database should be established for non-site-specific data used in the geoscientific characterization. The geoscientific model is prepared and presented with the aid of SKB's computer tool for visualization, the Rock Visualization System (RVS), and in the site description (see Figure 5-1). Standard procedures for version management provide traceability in model development.

After quality assurance of data and models (see Chapter 6), results will be open for scrutiny. Databases and model descriptions may possibly be posted on the Internet, provided data security is not jeopardized.

During ongoing site investigation, the different model versions, except the one on which permit application is based, are in principle SKB's internal products. Reports will, however, be made to the supervisory authorities during the course of the work. The model version that exists after the initial site investigation also comprises a part of the preliminary site description which is then presented. As information technology develops, computer-based presentations will presumably become increasingly sophisticated so that 3D movies of models can be shown to a larger public.

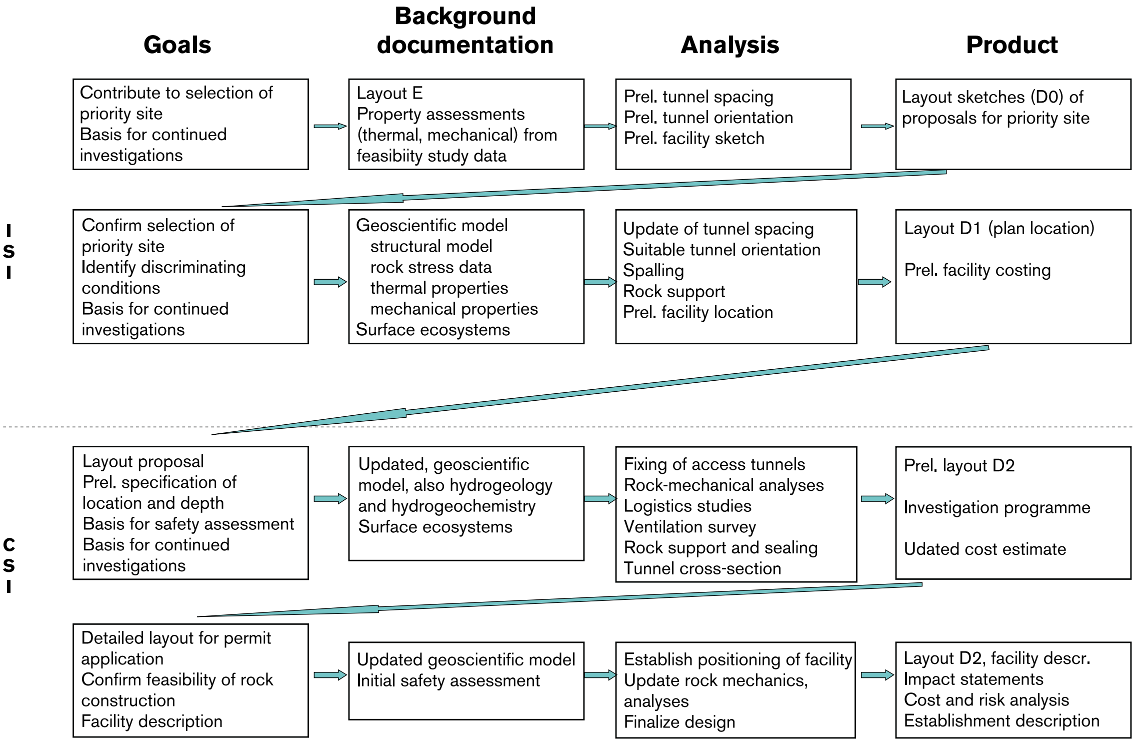
5.2 Design

When the site investigations are finished, the activity *design* shall have:

- presented one site-adapted deep repository facility among several analyzed and proven its feasibility,
- identified facility-specific technical risks, and
- developed detailed design premises for the detailed characterization phase.

The facility description is developed stepwise, as illustrated schematically in Figure 5-3. The non-site-specific facility description, called layout E, is available before the site investigations are begun. It is based on a generic coordinated proposal for the geometric design of the deep repository and serves as a basis for the continued site-specific design process. The final development step during the site investigation phase is layout D2, which is based on the information from the complete site investigation. In each step, various analyses are performed whose results are used as a basis for the detailed steering of the continued site investigation programme, as a basis for the safety assessment work and for the continued design work. The flow of background documentation, analyses and results is illustrated schematically by Figure 5-3.

The facility description also comprises one of the prerequisites for the preparation of draft documents for the rock and construction work as well as the preparation of programmes for layout-governing systems in the underground facility such as ventilation, rock drainage and electricity supply. Together with the layout-governing systems, the design of machines and vehicles that is proposed in conjunction with layout E provides a basis for the preparation of the facility description. The results of the site investigations are used in the design process to propose locations for the various facility sections, whereby the site-adapted layout of the deep repository is obtained.



	Goals	Background documentation	Analysis	Product
	Contribute to selection of priority site Basis for continued investigations	Layout E Property assessments (thermal, mechanical) from feasibiity study data	Prel. tunnel spacing Prel. tunnel orientation Prel. facility sketch	Layout sketches (D0) of proposals for priority site
ISI	Confirm selection of priority site Identify discriminating conditions Basis for continued investigations	Geoscientific model structural model rock stress data thermal properties mechanical properties Surface ecosystems	Update of tunnel spacing Suitable tunnel orientation Spalling Rock support Prel. facility location	Layout D1 (plan location) Prel. facility costing
CSI	Layout proposal Prel. specification of location and depth Basis for safety assessment Basis for continued investigations	Updated, geoscientific model, also hydrogeology and hydrogeochemistry Surface ecosystems	Fixing of access tunnels Rock-mechanical analyses Logistics studies Ventilation survey Rock support and sealing Tunnel cross-section	Prel. layout D2 Investigation programme Udated cost estimate
	Detailed layout for permit application Confirm feasibility of rock construction Facility description	Updated geoscientific model Initial safety assessment	Establish positioning of facility Update rock mechanics, analyses Finalize design	Layout D2, facility descr. Impact statements Cost and risk analysis Establishment description

***Figure 5-3**. Steps in the design work, background documentation, analyses and products.*

5.2.1 Design work during the initial site investigation

Preliminary layout sketches

When the first site-specific geoscientific descriptions are available, layout sketches (D0) are developed. These layout sketches take into account identified fracture zones and the requisite rock volume with reference to the thermal and mechanical properties of the rock. Several alternatives per area may be needed for the selection of a priority site. A preliminary assessment is made of what environmental disturbances and technical excavation-related problems may arise. Based on the sketches, it can first be judged whether the proposals for priority sites that are presented are suitable from an environmental viewpoint and large enough to accommodate the repository.

The background documentation for the analysis consists of the first geoscientific description (general site model version 0 and version 1.1), i.e. is based on feasibility study material and supplementary measurements from the surface and from percussion boreholes (see section 5.1). The layout sketches are based on interpreted regional fracture zones (lineament interpretation etc), local major fracture zones (whose location is highly uncertain at this stage), and estimated thermal and mechanical properties of the rock. Available experience of rock work in the area and estimates of rock stress directions and fracture directions are also utilized. It should be emphasized that the layout sketches are not based on information from great depth. Large changes can occur when the borehole information becomes available at later stages.

Based primarily on the general knowledge of the thermal and mechanical properties of the rock, an initial assessment is made of what may be a suitable spacing between deposition holes and deposition tunnels. A suitable tunnel orientation is chosen on the basis of e.g. estimated rock stress directions and observed fracture directions on the surface. The analysis is primarily performed as a check against previous general analyses. Check calculations may also be performed.

Preliminary layout sketches are produced where deposition areas are placed between identified regional and local major fracture zones with the respect distances indicated by stipulated criteria /Andersson et al, 2000/. The size of the deposition area is given by the number of deposition holes and the spacing between holes and tunnels that has been determined in the analysis. At this stage, the layout sketch consists of preliminary areas for deposition and operating chambers plus corridors for access tunnels and transport tunnels within the deposition area. The location in depth is specified within a relatively wide range. In view of the uncertainties concerning the locations of the fracture zones, detailed positioning of the repository is not possible, either horizontally or vertically.

With the guidance of the layout sketches, possible critical passages of access tunnels through fracture zones are identified. A preliminary assessment is thereby made of which technical construction-related problems may occur. The conditions for establishment of an operating area above ground and building of infrastructure on the ground surface, as well as other impact questions such as handling of excavation spoils, are studied and dealt with in the consultation process stipulated by the Environmental Code which is commenced after the site investigations have begun.

A preliminary assessment is made of where additional information is needed from investigations and geoscientific modelling. The layout sketch forms part of the initial background documentation for the preliminary safety assessment made within the safety assessment. During the work, material is provided for a number of sub-assessments in the safety assessment to illustrate the safety-related importance of a number of alternative facility layouts. Examples of questions related to long-term safety are:

- different solutions for transport and other communications with the surface (ramp or shaft),
- schematic positioning of ramp/shaft in relation to fracture zones, hydraulic gradient, rock stresses etc, and
- method and material for backfilling – particularly the question of the possibility of using the rock spoils for this purpose.

The work is concentrated on questions that need to be decided at early stages of the layout work (such as establishment area and choice of ramp or shaft for vertical access). Questions that can be decided at later stages are studied more superficially.

Preliminary facility description

When the investigations and the geoscientific modelling have led to a preliminary site model (version 1.2) based on the borehole information obtained in the initial site investigation, an initial site-adapted facility description with layout (D1) is prepared. One or more alternatives are prepared, depending on the situation on the particular site.

Type of access to repository level (ramp or shaft) is chosen preliminarily with reference to conditions on the sites in question. The requisite operating area above ground and its accesses are adapted to local conditions. The hydrogeological model and ecosystem model, together with the results of conventional geotechnical investigations, serve as a basis for proposals for routing of access roads to the deep repository.

Layout D1 consists of site plans above and below ground, including access ramps/shafts. Neither the location of individual tunnels nor the exact depth of the deposition area are determined, since the geological-structural model scarcely has sufficient information on the deep-lying fracture zones at this point. An assessment of suitable depth intervals with reference to rock cavern stability and groundwater chemistry is made, however. Depending on the conditions on the site, alternative layouts can be proposed for different depths. Since the tunnel directions in the deposition areas cannot be established at this point, different alternatives for access tunnels and a central area are drafted for a number of alternative tunnel directions.

Analyses of spacings between deposition holes and tunnels are updated. Available fracture statistics, results from initial rock stress measurements and estimated values of rock strength are used to forecast stability conditions, such as estimated risk of block breakout (wedge formation) or risk of other extensive rock breakout. Results of previous parameter studies are utilized, supplemented by check calculations using rock-mechanical models. The forecasts are used as a basis for revising suitable tunnel directions and updating tunnel and deposition hole spacing. Groundwater chemistry results are checked against established criteria to determine whether the salinity of the groundwater may limit the possible repository depth, see /Andersson et al, 2000/. The layout sketch is updated based on the results of the above analyses and the updated geoscientific model.

With the guidance of the layout and the geological-structural model, critical passages of tunnels through fracture zones are identified. The need for rock support is assessed. With the guidance of the hydrogeological model, an assessment is made of the sealing needs, particularly at passages of water-bearing fracture zones. Sealing needs are influenced by technical end environmental requirements.

The construction cost is calculated on the basis of layout sketches and assessments of rock support and sealing needs. Construction-related risks, including environmental impact, are estimated. A preliminary cost estimate is prepared. A preliminary analysis of the environmental impact of the construction of the facility is carried out.

Layout D1 is the document used by safety assessment to perform the preliminary safety assessment following the initial site investigations (see section 3.3). Furthermore, the need for supplementary function analyses is identified.

The layout and the identification of areas where more information may be needed are also used by the site investigation to make a detailed schedule of the different collection periods within the complete site investigation.

5.2.2 Design work during the complete site investigation

Facility description with layout for the deep repository

When the complete site investigations have come so far that the site models (version 2.1) have been devised, a facility description is developed that includes all facility sections, both above and below ground, with a layout (D2) for the deep repository. Each facility section is dimensioned to meet specified requirements on function, layout and interrelationships. Only one layout is devised for each site. Layouts above and below ground shall, however, allow some flexibility for further detailed adaptation. Areas for the deep repository's different facility sections are identified and largely finalized at this stage. Rock volumes reserved for deposition of canisters are chosen, and the locations and directions of the access tunnels are determined. The exact locations and direction of the deposition tunnels do not have to be known at this point in time, however. The exact locations of the deposition tunnels neither can nor need be determined during the site investigation, but are established in connection with detailed characterization and repository construction.

Premises for the various rock works such as requirements on rock support, sealing requirements or choice of material for backfill, i.e. *site-specific design criteria*, are determined preliminarily. The cost estimate and construction-related risk analysis (including environmental impact) are updated.

Preliminary boundaries for the horizontal and vertical positioning of the facility are determined with reference to geology and identified fracture zones, supplemented with information on rock stresses, groundwater composition and hydrogeology in the entire rock mass. The boundaries of the deposition area are updated with regard to respect distances from regional and local major fracture zones established after revised function analyses, taking into account the hydrogeological and mechanical properties of the rock. Areas that have been judged to have unsuitable properties (e.g. high permeability) are avoided. Repository depth is chosen primarily on the basis of the three-dimensional geometric structural information, and a check is made that there is no risk of spalling, other extensive rock breakout (see below) or undesirable water composition within the selected rock volume for the deep repository.

Corridors for the ramp and shafts are determined based on the geometric structural information, infrastructure on the ground surface and availability of areas on the ground surface judged suitable for placement of tunnel portals and above-ground operating areas. Environmental and safety viewpoints are taken into consideration.

A number of rock-mechanical analyses are carried out, such as:

- detailed thermo-mechanical sensitivity analyses for deposition holes and the rock between deposition tunnels, based on measured ranges of variation and estimated uncertainties in mechanical properties and boundary conditions,
- updating (choice of different alternatives) of suitable tunnel orientation based on stresses (levels and directions) and directions of local minor fracture zones and fractures within the rock blocks included in the selected deposition areas,
- updated stability and rock support forecasts based on updated tunnel geometry, updated stresses, stress directions and rock-mechanical properties,
- stability forecasts for deposition holes and deposition tunnels based on tunnel geometry, fracture geometry, rock stresses and the mechanical properties of the fractures, and
- optimization of cross-sections and directions for operating and disposal chambers in the deep repository.

The results of the analyses influence the main layout for the deep repository based on the number of deposition holes and the space requirements for other facility sections.

With the guidance of the layout and the geoscientific site model, critical passages of tunnels through fracture zones or other conceivable complicated areas are identified. Based on the rock-mechanical analyses, a judgement is made of the need for rock support measures. The hydrogeological model (and ecosystem model) is used to estimate sealing needs. Using the produced layout, system and logistics studies are carried out to prepare proposals for construction stages. Proposals for site-specific design criteria are prepared.

The construction cost is calculated on the basis of layout sketches with estimates of rock support and sealing needs. The uncertainties in the premises are estimated and their influence on the construction cost is analyzed. The analysis of the environmental impact of facility construction is updated.

The produced layout serves as a basis for the planning of where further borehole investigations should be undertaken. The main layout also serves as a basis for the safety assessment that is performed during the supplementary site investigation (see section 5.3).

Facility description with detailed layout

When the site investigations have been completed and a finalized version (version 2.x) of the site models has been prepared, a detailed layout (D2) can be finalized. The detailed layout has set boundaries for the horizontal and vertical positioning of the facility. Locations of ramp and shafts are fixed. Orientation of deposition tunnels is determined. Cross-sections and directions of operating and disposal chambers are updated.

A general plan is produced for the different facility sections regarding rock excavation and rock support and sealing needs. System studies and facility description are finalized. The impact of the construction work is described. The construction-related risk analysis and the cost analysis are updated.

The analyses that are carried out to produce the detailed layout are essentially of the same kind as those carried out to product the main layout (see above). The analysis is based on the final geoscientific site model.

The produced facility description and other background documentation are used as supporting documents in the siting permit application. The safety assessment (see below) is updated if the detailed layout deviates to an appreciable degree from the previously analyzed main layout.

5.3 Safety assessment

An evaluation of long-term radiological safety for the repository design proposed on the site is one of the most important tasks during the site investigation phase. Long-term radiological safety is evaluated with the aid of safety assessments. When the site investigations are completed, the activity *safety assessment* shall have:

- evaluated the long-term radiological safety of the planned deep repository based on reported investigation results and prepared repository layout.

Reports regarding safety are delivered on at least two occasions in the site investigation programme: once in the form of a *preliminary safety judgement* based on data from the initial site investigation, and once in the form of a *safety assessment* based on data from the complete site investigation. Furthermore, the preliminary assessments and analyses done within the framework of the safety assessment work are used in the planning of the continued investigations and the geoscientific modelling. Safety-related aspects of layout proposals or more detailed questions regarding the geometric configuration of the repository are analyzed and assessed, providing background material for the continued design work.

SKB recently reported the results of the safety assessment SR 97 /SKB, 1999a/. Since much of the background material for SR 97 is similar to the results that can be expected from a site investigation, many of the results from SR 97 can be used to quickly get an idea of what kind of results can be expected to be obtained from different data from the investigations. This permits quick, informal feedback from the safety assessment to investigations and design work throughout the course of the site investigation. The preliminary safety assessment, as well as the complete safety assessment, are, however, based on well-defined versions of the site model and layout.

5.3.1 Scope and coordination with other activities

The methodology and results from the safety assessment SR 97 form an important foundation for the work with safety assessments during the site investigations. A safety assessment is a very large undertaking which must be conducted in parallel with the investigations. During 2000, a survey will be made of all experience from the execution of, and viewpoints from the critical review of, SR 97. At that time, a timetable will also be drawn up for the development of the methods and tools used in the safety assessment in preparation for the analysis of the sites. No attempt is made in this report to predict what new findings may be available at the time of future safety assessments, however. The account is primarily aimed at clarifying how the safety assessment ties in with the activities of investigations and design in the site investigation programme. In all essential respects, however, SKB already has a methodology for carrying out safety assessments and has identified most essential processes that need to be analyzed. The site investigations supply data on the candidate sites.

The safety assessment can be said to consist of:

- a thorough description of the appearance or state of the repository system at an initial point in time, e.g. just after construction and closure,
- 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.

More concretely, the recently completed safety assessment SR 97 consists of the following elements:

- System description – a structured, general description of how internal processes influence the repository over time.
- Initial state – description of the appearance of the repository and its environs just after closure.
- Choice of scenarios – a number of different courses of events in the environs. 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 – analysis of the evolution of the repository for each of the chosen scenarios.
- Evaluation – overall assessment of repository safety. Confidence in the results in the light of the uncertainties that exist in the data underlying the assessment must also be discussed here.

Above all, the site investigations provide background material for describing the initial state of a site and confidence in this description. An evaluation and forecast of how the properties of the site change due to repository construction also needs to be done. The safety assessment receives different input data from investigations and design and then carries out thermal, hydraulic, mechanical and chemical analyses, as well as calculations of radionuclide transport. Figure 5-4 shows the steps in a safety assessment, where information from investigations and design are directly of use. The end product of the safety assessment is a safety report, which serves as a supporting document for an application for a siting permit for one of the sites.

Coordination with investigations

The geoscientific modelling essentially entails that the data observed in and around boreholes are extrapolated to three dimensions. Furthermore, an understanding of the site is built up, among other things of how the hydrogeochemical and mechanical evolution of the site has led up to the present-day situation. Both interpretation of data and analyses of the historical evolution of the site entail carrying out different kinds of model simulations.

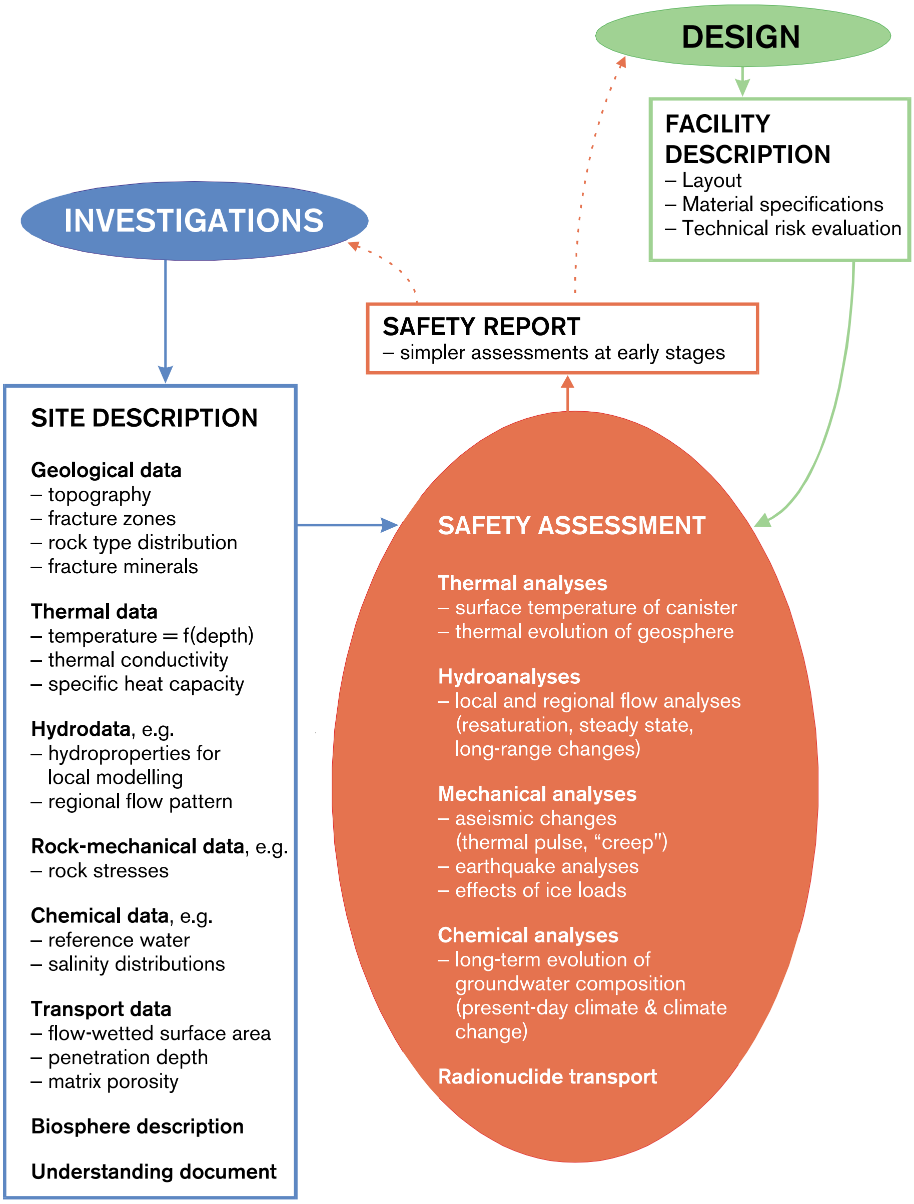


Figure 5-4. *The safety assessment receives input data from investigations and design. The data and analyses shown in the figure are examples. They do not comprise a complete list of what is included in a safety assessment.*

Data are delivered to the safety assessment in the form of the geoscientific models described in section 5.1. The models provide a three-dimensional depiction of the site and show e.g. geological structures plus mechanical, thermal, hydrogeological and chemical properties. Each version of these models also includes an evaluation of data quality, often in the form of a specification or discussion of uncertainties in the data. Alternative model interpretations are offered in certain cases. Furthermore, an understanding document is produced which describes in words the conceptual understanding of the site based on observed field data, extrapolations in space and model simulations, see section 5.1.2. This document is also an important background document for the safety assessment.

The distinction made between the geoscientific model simulation that is carried out within the framework of the activity *investigations* and the simulations that are done within the safety assessment should not be exaggerated. It is more a question of different model analyses being performed for different purposes than the development of completely different models. Regional flow simulations offer one example. Regional models are important in building up an understanding of the site, which can be said to be a geoscientific question, but the regional models also provide boundary conditions for local models in forecasts of the future groundwater flow in the repository area, which are used directly in the safety assessment. Simulations with the regional model must therefore satisfy the needs and interests of the safety assessment so that the results can, for example, be used as boundary conditions for the simulations with the local models of the future evolution of the repository which are performed in the safety assessment. In so far as the studies also include the historical evolution of the site (to demonstrate understanding of how the present-day situation arose), such studies should be coordinated with the safety assessment's need for studies of the future evolution of the repository (which are required in the assessment of future safety).

In other words, the distinction between geoscientific model simulation and model simulation for the direct needs of the safety assessment should not be interpreted too strictly. The distinction is primarily made to emphasize the fact that the simulations have different purposes (to interpret data and understand a site, versus to make forecasts of the future evolution of the site). The description of the site and confidence in the data comprise central aspects of the safety report as well. Normally, the safety assessment therefore also governs the geoscientific model simulation. An endeavour will be made to use the same modelling tools (and the same persons) to carry out both the geoscientific simulation and the associated forecasts that are needed directly in the safety assessment.

Coordination with design

A layout proposal is one of the products delivered to the safety assessment by the principal activity *design*. As a basis for the proposed layout, design has used e.g. preliminary respect distances to fracture zones, thermal calculations or estimates, and mechanical analyses of the stability of the deep repository in conjunction with rock abstraction and facility operation. Early versions of layouts and other repository design documents may also contain alternative locations for e.g. shafts and ramps or proposals for site-adapted backfill materials.

The safety assessment studies the safety of the repository for the proposed layout. Function analyses are carried out to shed light on specific questions. If uncertainties or safety margins are judged to be less satisfactory, a discussion is initiated with design regarding how the layout should be modified. Results of function analyses are used for continued choices and dimensioning principles in the design work.

Just like between "geoscientific modelling" and "safety assessment", there is no obvious distinction between the modelling that is done by *safety assessment* and the calculations that are performed within the framework of the design work. The results of the safety assessment's thermal analyses (surface temperature of canister), hydraulic analyses (e.g. transport resistance from individual deposition holes) and mechanical analyses (influence of heat load, earthquake calculations) may be used to modify the layout. Design's analysis of heat evolution, water seepage and mechanical stability of tunnels during the construction and operating phases naturally needs to be coordinated with the safety assessment's modelling of similar processes. Some overlap of different modelling efforts must be accepted. Here again, the modellings are done for different purposes, and it may sometimes be expedient to use different approaches in safety assessment and construction analysis.

5.3.2 Preliminary safety judgement after initial site investigation

After initial site investigations have been carried out, the site-specific information in the form of the preliminary site models (version 1.2) and the preliminary facility description (layout D1) are relatively limited. The task in this phase is to judge whether it is reasonable to proceed with a complete site investigation or whether the site should be abandoned in favour of another site.

As far as long-term safety is concerned, the body of data following the initial site investigation is not expected to be sufficient for a comprehensive safety assessment. The judgement of the suitability of the site for continued investigations is therefore based primarily on:

- comparisons with the requirements and criteria formulated in /Andersson et al, 2000/,
- comparisons with the conditions on the three sites analyzed in SR 97 and what can thereby be said about expected analysis results, and
- simple analytical transport calculations of the kind carried out in SR 97, with whatever new site-specific data are available.

SR 97 analyzed three sites with granitic bedrock with slightly varying conditions as regards geology, groundwater flux, water chemistry, nearness to coast, northern or southern situation, surrounding biosphere, etc. It is reasonable that the areas that are subjected to site investigations should not differ too much from at least one of the sites in SR 97 in terms of e.g. groundwater composition, distance to coast and predominant biosphere type. The analysis results from SR 97 should thereby be able to be used for preliminary safety judgement after the initial site investigation.

Even though the preliminary safety assessment is based on data and layout developed when the initial site investigations have been completed, considerable work proceeds throughout the phase as well as before data and layout are available in official versions. Early versions of the site model and associated layout sketches are judged continuously. Function analyses or assessments are carried out to answer questions asked by design, see section 5.2.1. Mostly, however, this time is devoted to preparing activities for the complete site investigation, for example in the form of methodology development.

Feedback to investigations and design

The preliminary safety judgement is used as a basis for the planning of the investigations for the complete site investigation. The judgement can, for example, identify areas or parameters where the uncertainty needs to be reduced by means of further investigations and geoscientific modelling. Results of partial analyses or function assessments (e.g. regarding positioning of ramp and shaft, backfill material) are used as a basis for the continued design work during the complete site investigation.

5.3.3 Safety assessment after complete site investigation

The complete safety assessment is based on the final site models (version 2.x) and the detailed layout (D2) that have been prepared when the investigations have been completed. In this phase, all activities in Figure 5-4 shall be carried out, along with everything else included in a safety assessment. The information set that will exist after the complete site investigation provides sufficient material for an analysis of at least the same scope as the safety assessment SR 97. The methodology and knowledge base for a safety assessment are developed constantly, and to the extent that new findings and methods are available, they can be used in the assessment, which shall be based on site investigation data. Ongoing or planned research and development projects that have a bearing on the safety assessment are described in RD&D 98 /SKB, 1998/. A number of points where the background material for the assessment can be developed and improved are also identified in SR 97. SR 97 will undergo a comprehensive external review during 2000, which is also expected to lead to proposals for development.

To provide opportunities for meaningful feedback to other principal activities, the detailed safety assessment work is begun from the first complete set of the site models (version 2.1) with associated preliminary layout (D2) for the deep repository. The parts of the safety assessment that are not affected by site-specific conditions are finished early. Areas where the assessment may be influenced by new data are identified, but the assessment is carried out with the first complete set of data. The assessment is revised to the extent that later versions of the site models or the layout entail essential changes.

Feedback to investigations and design

The results of the analyses that are performed on the basis of data from the preliminary complete site models (model version 2.1) for the chosen main layout may call for additional investigation campaigns, if the site models need to be updated or if the layout needs to be revised. The crucial question for deciding whether additional investigations or further modification of the layout are needed is whether the uncertainties are deemed to be too great in relation to the assessed safety of the repository.

5.4 Coordination

During the site investigation, the various principal activities will require information from each other, see Figure 5-5. When the activity *investigations* has gathered and interpreted new data for revised models of the site, the layout can first be modified and the *safety assessment* can then be revised with reference to the new site models with associated layout. In the work with the layout and the safety assessment, requests arise for new data or data with greater precision. Furthermore, the results of the safety assessment may require revision of the layout.

The interdependence between the different principal activities requires coordination to ensure that:

- safety assessment and layout are based on consistent versions of the site models,
- unnecessary overlap of modelling work is avoided,
- questions or judgements that are made within one principal activity are actually answered or applied in the other activities, and
- the work is terminated when the goals of the various principal activities have been attained.

This coordination comprises an important part of the quality assurance of the site evaluation, see Chapter 6. Figure 5-5 shows a reasonable number of feedbacks between the different principal activities. Fewer or more feedbacks may be needed for a particular site. Each new version of site model, layout and revised safety assessment entails extensive work. There is therefore good reason to limit the number of model versions and focus the work on achieving high quality in the versions and revisions that are actually done.

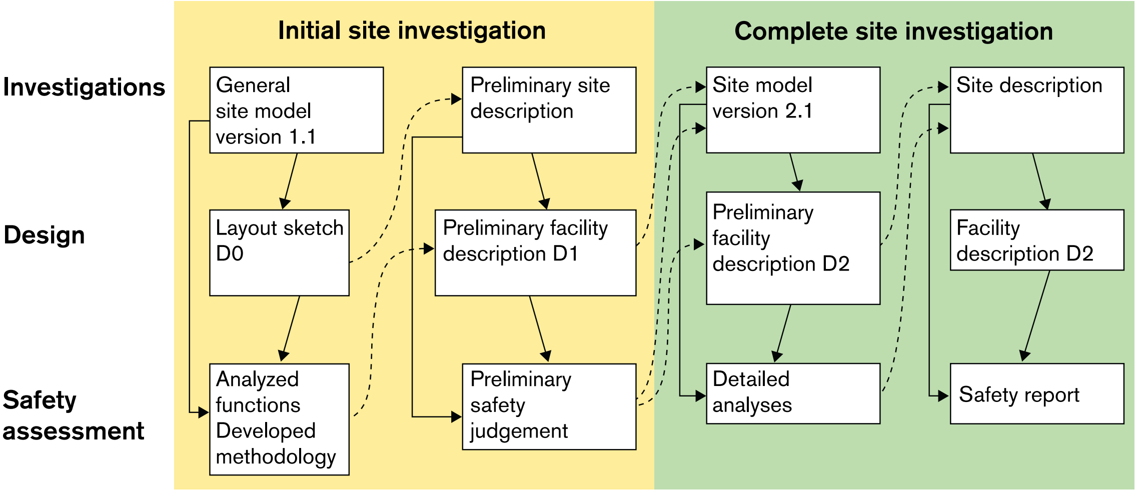


***Figure 5-5.** Products that are developed within one principal activity are in turn used as a basis for developing new products within the other principal activities.*

6 Quality assurance

SKB's strategy for quality assurance of the site investigations is presented in general terms in this chapter. By "quality assurance" is meant here both doing the right things, and doing things in the right way. It concerns everything from formulation of programmes and plans to execution of investigations, design and safety assessment. Having full traceability in how data and results are used and what decisions are based on is essential and requires good procedures for documentation and archiving. Furthermore, systematic procedures are required in order to be able to maintain a good overview of results and be able to take corrective action where needed in the relatively extensive operation which the site investigations will comprise.

6.1 Central quality aspects

6.1.1 Organization

SKB's plans regarding the organization of the site investigations are discussed briefly in Chapter 7. The design of the organization naturally influences details in the quality assurance work, but not overall strategies. The operation will be conducted in the form of projects, sub-projects and activities. Support functions within science, technology and administration will be built up at different levels in the organization. The rules of procedure will be defined in the broken-down organization. Clear purchaser and supplier roles will be defined for internal or external relations.

The different units that are established will have relevant delegated responsibilities for quality assurance procedures, including responsibility for assuring the right competence by means of e.g. training. Quality follow-up can be performed by the company, project or sub-project management in different ways, where quality auditing is a natural ingredient.

6.1.2 Quality strategy

SKB works with an integrated quality management system with procedures in accordance with ISO 9001 and environmental management procedures in accordance with ISO 14001. The system will be implemented when the site investigations are begun.

The most essential quality aspect is that the right things are done. Previous chapters have presented how SKB intends to execute site investigations within the framework of the principal activities *investigations*, *design* and *safety assessment*. The programme describes how site-specific knowledge will be obtained and what results will be produced. What properties are to be determined and how the information is used to decide whether a safe final disposal can be carried out are based on the results of SKB's previous studies and experience, of which the compilation of parameters /Andersson et al, 1996/, the compilation of requirements and criteria /Andersson et al, 2000/ and the most recent safety report SR 97 /SKB, 1999a/ are the most important for this programme.

This has been mentioned previously, but is repeated since these reports provide the main motives for the investigation and evaluation programme. Discipline-specific and site-specific programmes will be presented later as a complement to this programme. Taken together, it is these programmes and their subsequent critical review and acceptance that comprise the quality assurance that the right things are done.

SKB as a purchaser organization will have many suppliers in conjunction with the site investigations. Systematic supplier assessments and contract reviews will be performed in accordance with SKB's purchasing procedures. Strategies will be devised for quality audits for both internal and contracted resources so that they can be established and implemented early in the different parts of the organization.

6.1.3 Safety, health and environment

Prior to the start of each sub-project, the possible environmental risks of the different activities will be identified with the support of project-wide environmental assurance procedures. As regards the external environment, systematic support is provided in the information that is acquired within the framework of SKB's investigations of surface ecosystems. Procedures for consultation processes are one example of quality-assured methods to find acceptable solutions from an environmental point of view. It is vital for human health and safety that hazardous substances be avoided. Fuels and oils for field equipment and solutions for mobile field laboratories are examples of substances that must be handled, but in a controlled manner. Equipment is inspected with regard to safety and environment and rectified where necessary to prevent injuries to human beings and the environment.

6.2 Controlling documents

SKB's system for management and quality is structured like a pyramid. At the top are policies and corporate procedures for such functions as purchasing, accounting, internal audit, nonconformance management and project control. In addition there are department-specific procedures and, for major projects such as upcoming site investigations, *project manuals* are compiled for management of project operations. Such manuals shall contain instructions on how project operations are to be conducted and documented. Organization, responsibilities and powers for different positions, how decisions are made and how reports are to be approved are examples of the contents of these instructions. As regards the technical operation, the manual provides information on what controlling and accounting documents are to be used.

With reference to Figure 6-1, a schematic overview of the documents that control the execution of the site investigations is provided here.

SKB's operation plans and the *programmes* for site investigations that have been presented serve as the control documents. The programmes give an account of the purpose of the different operations, above all with regard to what information is to be gathered, and how the analysis, evaluation and design work is to be executed. Furthermore, the programmes describe which methods are to be used to do this and how the results are to be reported. These technical programmes must satisfy the quality requirements in terms of "doing the right things" (can be said to answer the questions "what" and "why"). This quality assurance is achieved partly by SKB's internal oversight and partly by external oversight by government agencies and other scientific experts.

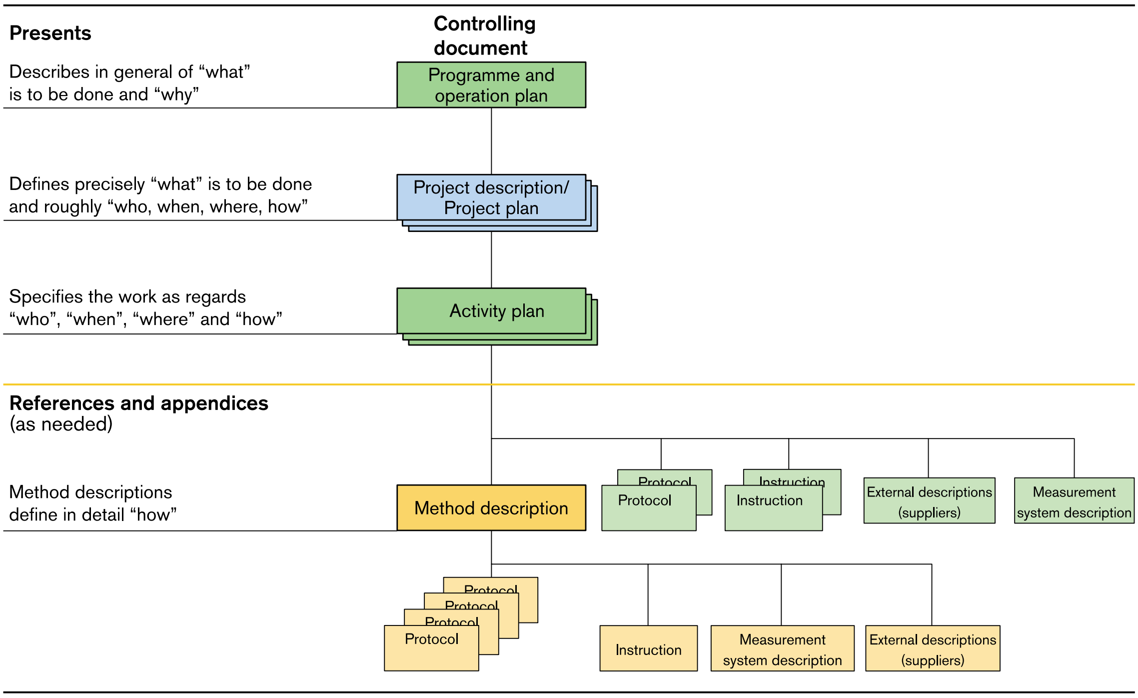


Figure 6-1. *Schematic overview of documents for control of the execution of the site investigations.*

The site investigations will, as before, be conducted in project form. A *project description or project plan* that identifies the expected results will be drawn up for each project or sub-project. These control documents can be said to provide precise answers to the question "what" and general answers to the questions "who", "when", "where" and "how".

Within the framework of planned projects, the operation is normally broken down into activities. *Activity plans* control in detail how the work is to be executed and documented based on the quality aspect "doing it in the right way" and can be said to provide precise answers to the questions "who", "when", "where" and "how". The means of reporting results (protocols, data files and reports) shall show clearly who has been responsible for executing different parts.

The *method descriptions* contain method-specific instructions for "how" methods are to be carried out. Method descriptions comprise part of the base of the "quality pyramid" and are mainly prepared for investigation methods. Not least essential is to specify what information sets are to be produced, how the work is to be documented and how results are to be archived. Accurate and purpose-suited method descriptions ensure that a method will be applied correctly and performed in the same way every time.

Examples of other instructions that are essential for the execution of investigations are manuals and procedures for the handling, calibration and maintenance of equipment. There must also be established procedures for what data are to be entered in SICADA and how their storage is to take place.

6.3 Documentation and traceability

Large quantities of data are generated and managed during the site investigation phase. In most cases, data are used in several analysis and evaluation steps, where the results from one step are used as input in the next step, and so on. This applies in the preparation of site descriptions as well as in design and safety assessment, where the investigation results are used. As in other production chains, the end result is dependent on the quality of each link. An important basic prerequisite for achieving full control and traceability in the entire chain is to generate adequate documentation of input data, process data and output data for each link should in accordance with the following:

- **input data**: unambiguously identify the body of data used for the activity;
- **the process**: fully document the execution of the activity;
- **output data**: unambiguously identify the results produced by the activity.

As far as the quality of the measurement results is concerned, the principle is that the one who executes an activity (the supplier) bears responsibility for ensuring that the supplied products meet the requirements laid down in the activity's controlling documents, i.e. the product must be quality-assured at delivery. A delivery inspection is performed at reception, mainly to ensure that all documentation has been received. SKB also carries out quality auditing to an appropriate extent.

6.4 SKB's central computer tools

6.4.1 SICADA's role as a quality-assured database

The main purpose of a central database is that collected site data should be accessible from one source. The information is thereby shared by all users who work with analysis, evaluation, interpretation and modelling.

Not just primary results (measurement data, directly calculated values), but also information on the activities that generate these data as well as activities that might affect measurement data, are stored in SICADA (Figure 6-2). Each activity is documented as to where and when it was executed. The results are then linked to each activity, along with particulars on who executed the activity.

There are a couple of ground rules for SKB's data management and use of SICADA. In the first place, only quality-controlled data may be stored in SICADA. Archived information must be maintained in accordance with quality-assured procedures. The second ground rule is that only data from SICADA may be used for interpretation, analysis and modelling of the investigated sites. Retrieval of data is followed by a log file, by means of which the same data set can once again be retrieved from the database if necessary. This makes the origin of the data set unambiguous. Traceability for processings, from original data source to finished results, can be assured in this way.

Investigation data from the site investigations will be collected in SICADA in accordance with the existing main structure. An general principle is that all investigation results are to be stored in the form of raw data. Processed data will, however, also be stored in SICADA when an accepted method for interpretation is available. Data are sorted in a hierarchical structure, according to discipline and type of measurement. Furthermore, data are linked to the activity that produced them. The site-specific databases will be

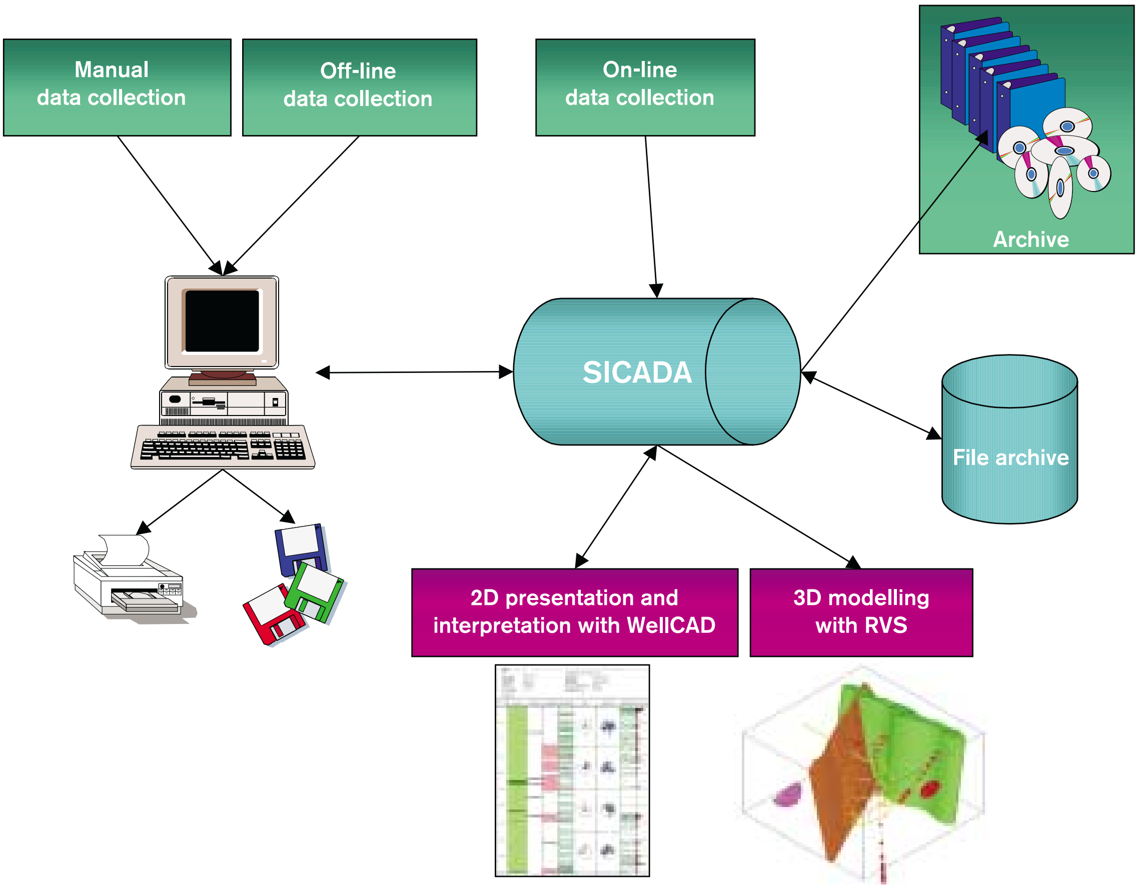


Figure 6-2. SKB's database SICADA with associated functions.

built up gradually. The idea is that produced and quality-assured results from each measurement should be entered into SICADA without unnecessary delay.

The vast majority of data are stored in tables in SICADA. Data can then be searched for and retrieved on-line from these tables. Certain special types of data are stored in SICADA's file archive, which means that back-up and maintenance are performed according to the same procedures, but that data must be ordered. This applies, for example, to data that are read-only and are processed by special programs, e.g. radar data. It also applies to raw data sets that are so large that it is more appropriate to store them on e.g. CD-ROMs. In any event, the existence of data shall be recorded in SICADA with a reference to the other archive.

The vast majority of data in SICADA consist of measurement data or results from calculations based on measurement data. Results from evaluations based on measurement data from one or more methods are not usually stored in SICADA, since they comprise interpretations (model descriptions) of the properties of the site.

Data can be exported in various formats from SICADA, and different programs can be linked to SICADA. Examples of such programs are everyday ones such as Excel, and special programs such as RVS and WellCAD.

SICADA is SKB's own database, but is in principle open to both internal and external users. This is important in order to enable SKB's results to be checked, since the data are only available in SICADA.

6.4.2 GIS

As a complement to SICADA, quite a bit of data will exist in GIS (Geographic Information System) databases. GIS is thus in this context another archive for digital data to which reference is made from SICADA. GIS is not just a database, but also a processing and presentation system. In the site description, GIS information (preferably 2D) will be linked to RVS for further modelling in 3D.

6.4.3 RVS

SKB has developed a geometric rock modelling system based on the three-dimensional CAD system Microstation. It is called RVS (Rock Visualization System), which also suggests its usefulness for presentation and demonstration of models. RVS is the tool that is used to construct geometric models, which comprise a common ground for the discipline-specific models, see section 5.1. RVS will also be used as a planning tool for boreholes, which improves the quality and facilitates the choice of borehole position and direction in order to ensure that the right portion of the rock volume is reached. Not least essential is the fact that design will use the same rock model to devise site-specific layouts.

RVS has been developed with effective data links to both SICADA and GIS, and in connection with the modelling work, data sets are imported directly from SICADA. In connection with the geometric modelling, geometric features such as fracture zones and rock units are identified. The properties to be included in the relevant discipline-specific model are then assigned to these features for each discipline. RVS models are strictly version-managed, and the data that have been used and how the interpreted properties have been determined are shown for each alternative model or version. This makes it possible to build up what can be termed a model database with the model versions that are saved.

The geometric RVS model will also serve as a basis for numerical model calculations as well as for simulation of groundwater flow and nuclide transport. It is then essential from a quality point of view that these model calculations be based on the same geometric frameworks as the descriptive models.

RVS is in the true sense more of a modelling tool than a quality assurance tool. However, the system is of very great importance for the quality of the geometric models and furthermore comprises a common point of departure for other geoscientific models, repository layouts and the modellings that are done within the framework of safety assessment, which guarantees that the geometric framework will be used consistently.

7 Organization, resources and timetable

7.1 Introduction

When SKB enters the site investigation phase after 2001, extensive investigations will be commenced of surface ecosystems, soil cover and bedrock, including the drilling of boreholes down to a depth of around one kilometre. In this phase, detailed studies will also be performed of how the facilities and transport infrastructure can be designed and realized, as well as what the environmental consequences will be. A site investigation entails yet another establishment on the site in question and will have some physical impact in the form of boreholes and field activities for several years. The work requires that SKB as an organization must adapt to the new requirements. This chapter discusses, from the perspective of technical investigation and evaluation, what requirements will be imposed on the new organization and what resources are required. A general timetable for the execution of the investigations is also presented.

Organizational aspects are an important part of the preparation work and the programme writing that is being pursued prior to the site investigations and will continue after them as well. This involves estimating the time taken by different activities during the investigations, identifying interactions between these activities, optimally utilizing measuring equipment between boreholes and sites, handling of large data quantities in conjunction with collection and evaluation, quality control, etc.

7.2 Organization and resources

The organization set up for the site investigations will be used to execute the activities that have been presented in Chapters 2 to 6 on at least two sites. A number of technical principal activities (investigations, design and safety assessment) will execute their tasks and interact so that different decisions can be made in the course of the investigations and so that efforts can be focused on what is essential. The activities are highly dependent on each other, and it is important that the interaction be good. These are the premises that govern the organization as well as the human resources that are required for execution.

The continued discussion of a possible organization and the requisite resources is best carried on from the perspective of an overview of various functions that are required in the site investigation phase, see Figure 7-1. This outline is relatively general, and further detailing will comprise a natural part of the continued preparation work.

It should be emphasized that the functions shown in the figure are those required in the organization and not human resources. The total number of persons required on each site is probably around twenty. One of the crucial organizational questions is the balance between the central and local functions and the interplay between them. It is important to have a strong organization on the site. It is on the site that the investigations must be executed and adapted to the special conditions prevailing there. The investigations presuppose access to the land for drilling and investigations and for some road construction. Great consideration must be given to the environment on the site so that the

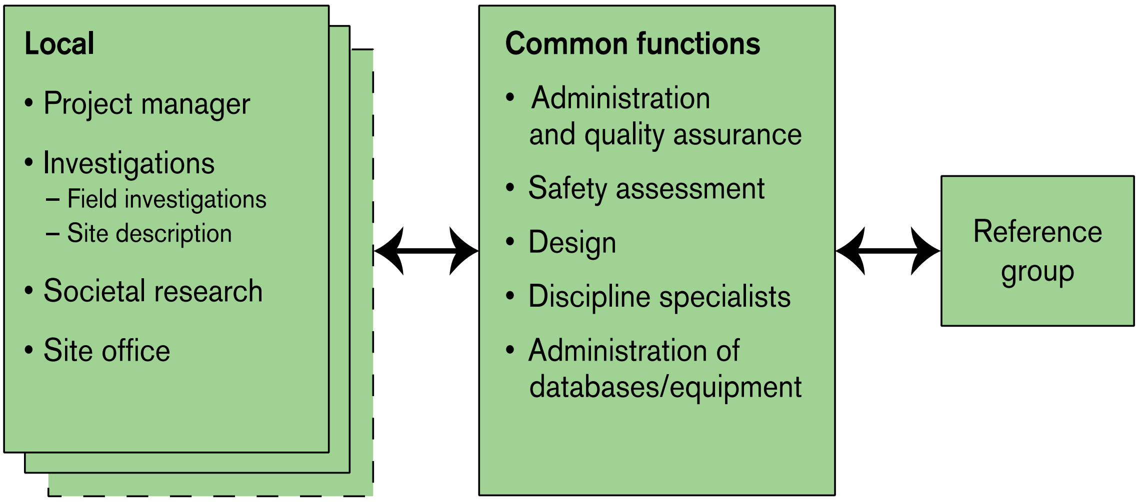


***Figure 7-1.** Overview of the functions required for the execution of site investigations on at least two sites, with an emphasis on the technical activities.*

invasive work entailed by drilling and other field activities is limited to a minimum, see Chapter 2. A project manager is appointed with total responsibility for investigations and contacts with the municipality, the public and the media. Measurement, quality control, data management and analysis of measurement data to build up the necessary site-specific understanding involve a great deal of local work. Among the human resources required for the investigations locally are: chief geologist, hydrogeologist, hydrochemist, RVS/SICADA operator, field measurement leader, measurement inspectors, computer operator, service technician and IT support personnel.

At the same time as the activities are managed locally so that the necessary body of data is collected for assessing the suitability of the site, the different sites must be investigated and evaluated in a similar manner. Coordination of investigation tasks, evaluation, design and safety assessment is necessary during ongoing investigations, even though much of this is controlled in the programmes that will be available prior to the execution of the investigations. Common functions also include discipline specialists within different geoscientific disciplines, quality assurance, overall investigation management, and planning of coming detailed characterization. In general, the organization, both centrally and locally, shall be structured for the best possible interdisciplinary collaboration (applies to both geoscientific disciplines and the principle actors during the site investigation) for the best possible integrated description of the sites. A principal task for the common coordination and evaluation function is to prepare the application for a siting permit that has to be submitted to the Government.

Besides the permanent organization shown in Figure 7-1 (altogether about 75 persons for two sites) there are also a considerable number of experts, consultants and contractors. While the permanent organization mainly manages and evaluates, external personnel are contracted for most of the practical work (drilling, field measurements, analyses, numerical modelling, etc). The resource requirement here is related to the investigation methods and associated measurement systems that will be used, see Appendix.

7.3 Timetable

A site investigation is a relatively extensive operation in the field that will last for several years. Figure 7-2 shows a picture of the overall timetable for the site investigation phase. The continued preparation work includes estimating the times required for field work and detailed planning of execution.

It is estimated that the initial site investigations can be commenced in the beginning of 2002 and will last for 1½–2 years. The time required is projected to be different for the different sites because the conditions and level of knowledge are different. To enable the resources to be utilized efficiently, the timetables for the investigations at the different sites will be somewhat staggered, so that the same activities will be held 4–6 months apart at the different sites.

In the execution of the complete site investigations, drilling will take place in several stages, where 3–4 deep boreholes are drilled simultaneously. This is followed by measurements and evaluation of the results. Each drilling stage is estimated to take around one year. After the last drilling stage, a summarizing and comparative evaluation of the different sites is carried out and a permit application with underlying documentation is prepared. This means that the duration of the complete site investigations can be estimated at 3½–4 years.

An application for siting and construction of the deep repository on one of the investigated sites pursuant to the Nuclear Activities Act and the Environmental Code will be submitted to the Government and the Environmental Court, respectively. The supporting documentation will then be examined by the authorities and the application reviewed by the Environmental Court. The time required for this is difficult to predict, but is estimated at about two years, which means that the site investigation phase in its entirety is projected to last about 7–8 years.

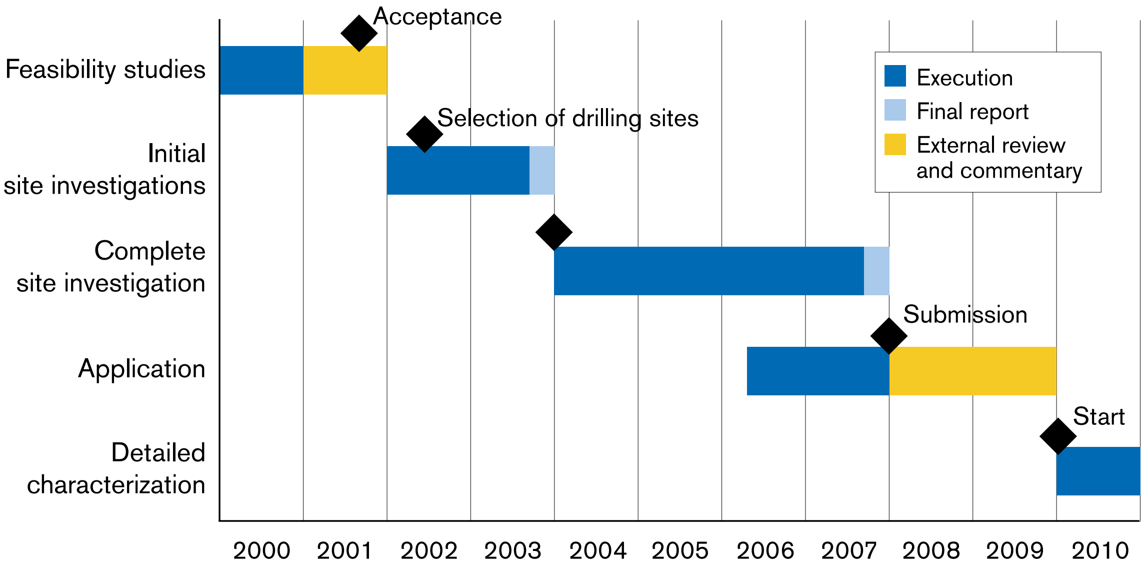


Figure 7-2. Overall and preliminary timetable for the site investigation phase in relation to preceding feasibility studies and subsequent detailed characterization. The timetable is based on the assumption that two sites are investigated.

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Appendix

Description of investigation methods

Investigation methods that are available and may be used during the site investigation phase are presented here. Which methods will actually be used will be clarified in coming site-specific programmes. Development of investigation methods is under way.

For a description of all methods used that contributed to the geoscientific characterization of Äspö in conjunction with the pre-investigations, see /Almén et al, 1994/.

Table B-1. Methods for surface ecosystems

Method	Information
Methods for surface ecosystems	
Land	
Vegetation mapping • Collect existing material • Aerial photograph interpretation • Map interpretation • Field check and inventory of land/brush – layers • Cultural landscape • Key habitats in forestry and agricultural land • Monitoring	• Vegetation and biotope map • Forestry • Quantity • Production • Rotation • Age structure • Agriculture • Production crops • Vegetation type • Key habitat • Population/production • Species of vascular plants, fungi, lichens, mosses and algae • Red-listed species
Fauna mapping • Collect existing material • Area assessment • Area inventory • Monitoring	• Species requiring consideration • Hunting (allocation and felling statistics) • Species (number/occurrence) • Biomass • Production • Red-listed (species/number) • Toxic pollutants/radionuclides
Soil sampling • Existing material from SLU • Possible supplementary sampling by SLU • Monitoring	• Soil • Soil chemistry • Soil (type and thickness) • Toxic pollutants/radionuclides
Mineral soil mapping, see Geological methods	• Elevation difference • Land uplift/Shoreline displacement • Stratigraphy • Quaternary deposits • Exposed rock
Aquatic	
Bottom mapping • Vegetation/animal zonations • Bottom type distribution • Monitoring • Annual cycle	• Vegetation zone map • Lake types • Sediment type • Oxygen concentration/Oxygenation • Stratification • Light conditions • Turnover/Currents • Degree of exposure
Sampling • Water fetching • Seining • Probes, oxygen, salinity, pH, light and temp. • Bottom sampling with scraper, divers etc • Production measurement • Monitoring • Annual cycle	• Species compositions and quantity of fauna and flora • Production • Water chemistry • Water physics • Lake types • Sediment type • Oxygen concentration/Oxygenation • Stratification • Light conditions • Temperature • Toxic pollutants/radionuclides • Turnover/Currents • Degree of exposure

Method	Information
Fishing • Compilation of existing knowledge • Net fishing • Electric fishing • Echo sounder • Monitoring	• Species composition • Toxic pollutants/radionuclides • Fishing licences, catch, professional fishermen
Bathymetric measurements • Sounding • Bottom sediment stratigraphy	• Morphometry
Water turnover measurements • Modelling of runoff • Flow measurement • Current measurement • Modelling of currents • Monitoring • Annual cycle	• Water flows • Currents
Climate/hydrology	
See meteorological and hydrological methods	• Ground frost/ice • Number of days with ground frost • Frost depth • Ice formation • Ice break-up • Wind force • Wind direction • Air pressure • Sunshine • Hours of daylight • Insolation, angle • Vegetation period • Length of season (days) • Precipitation • Runoff • Temperature • Evapotranspiration • Water level • Humidity • Water divide • Recharge and discharge areas
Man	
Data collection from feasibility study material and other databases	• Outdoor recreation • Berry and mushroom picking • Animal husbandry, meat production • Number and location of farms • Farmed area • Dietary habits • Reserve, protected area, area of national interest, etc • Type of industrial plants • Location of industrial plants • Area of industrial plants • Development plans, land • Number of residents, permanent/secondary • Employment of residents • Dietary habits of residents • Area history • Ancient monuments • Transportation • Societal development • Demographics

Table B-2. Geological methods

Method	Information
Geological methods **Surface geological methods**	
Image analysis topography/lineaments • aerial photograph interpretation • analysis of digital elevation database	**Lineament map** • large-scale tectonic structures • regional and local structures
Mineral soil mapping • aerial photograph interpretation • field mapping • sampling • investigation of bottom sediments (lake, sea)	**Mineral soil map with description** • Quaternary deposits, soils • thickness of soil cover • identification of recipients • neotectonic indications • interpretation basis for surface ecosystems • interpretation basis
Bedrock mapping • rock outcrops, rock cuts • exposed rock surfaces • sampling • soil/rock drilling with core sampling from rock surface	**Bedrock maps with descriptions** • rock type distribution • rock type description • plastic structures • brittle structures • neotectonic indications
Neotectonics / Rock movements	
Neotectonics – observations and long-term monitoring • geological/topographical observations in soil and rock • seismic observations/monitoring • analysis of geodetic data – GPS networks and precision levelling – land uplift data – deformation measurements	**Indicator phenomenon** • neotectonic indications (postglacial faults) • seismic activity (stability) • slow tectonic movements and block displacements
Geological borehole investigations	
Percussion drilling – investigation of drill cuttings and MWD • visual examination • sampling for mineralogical analysis • MWD	**Basis for GBD** (see below) • rock type boundaries • fracture zones
Core drilling – mapping of drill core with BOREMAP • based on BIPS logging (if done) • geological description of drill core • sampling of rock matrix and fracture-filling minerals for lab analyses (see below)	**Basis for GBD** (see below) • rock type distribution • rock type description • plastic structures • location/orientation of fractures • properties of fracture surfaces
Sample analyses • microscopic analysis • x-ray diffraction • x-ray spectography • petrophysical analysis • rock-mechanical analysis • dating	**Analysis results** • mineral composition • chemical composition • density, porosity, susceptibility, etc • see rock mechanics • age
Geological Borehole Documentation (GBD) • Geological mapping along borehole: – BOREMAP mapping – examination of drill cuttings – MWD – interpretation support from geophysics – interpretation support from sample analyses – statistical processing	**Geological description along borehole** • rock type distribution • rock type description • plastic structures • location/orientation of fractures • properties of fracture surfaces • statistical analysis of fractures • interpreted fracture zones

Method	Information
Geophysical methods	
Surface geophysical methods	
Airborne geophysics (incl. helicopter)	**Airborne geophysical maps:**
• magnetic methods	• regional and local structures, rock types
• electromagnetic methods	• regional and local structures
• radiometric methods	• rock types
Geophysical ground measurement (different scales)	**Geophysical maps, interpretation basis for**
• gravimetry	• rock types
• magnetic methods	• rock types, structures
• resistivity (CVES)	• structures, (porosity)
• electromagnetic methods (VLF, slingram)	• structures
• transient electromagnetic measurement (TEM)	• structures, deep saline groundwater
• seismic refraction	• structures
• seismic reflection	• subhorizontal structures
• ground radar	• structures, soil depth
Geophysical borehole methods	
Geophysical borehole logging	**Interpretation support for GBD** (see geology)
• caliper	• borehole status, geometry
• radiometric methods (natural gamma, neutron, gamma-gamma)	• rock type parameters
• electrical methods (resistivity, point resistance, liquid resistivity)	• rock type parameters, structures, groundwater salinity, hydraulic conductors
• magnetic methods	• rock type parameters , structures
• sonic	• rock type parameters, structures
• temperature	• rock temperature, water-bearing fractures
Borehole radar	**Interpretation support for structural model in RVS** (see geology)
• reflection survey	• structures (local major and local minor)
• tomography	• same (within about 100 m from borehole)
Borehole seismic surveys	**Interpretation support for structural model in RVS** (see geology)
• VSP (Vertical Seismic Profiling)	• structures (regional, local major and local minor) within up to 500 m from borehole
• reflection survey	
• tomography	
Borehole Image Processing (BIP)	**Image of borehole wall**
• BIP system	• basis for GBD (see geology)
	• rock types
	• location/orientation of fractures
	• borehole status
Geodetic methods	
Coordinate system	
Base coordinate system	**Positioning structure**
• RAK national systems are used	• X, Y, Z coordinates
Setting-out and position measurement	
Position measurement with traditional method or GPS	**Coordinate positions**
• measurement profiles	• X, Y, Z (RAK)
• measurement points/sampling points	• X, Y, Z (RAK)
• borehole	• X, Y, Z (RAK) and aiming
Borehole positioning and deviation measurement	**Positions along borehole**
• length from drilling	• borehole length
• borehole deviation	• X, Y, Z (RAK) against borehole length
• length marking and calibration in borehole	• length-corrected measurement points

Table B-3. Rock-mechanical methods

Method	Information
Investigation of rock stresses	
Rock stress measurements	**Rock stress results**
• overcoring	• size and direction; 3D method
• hydraulic fracturing	• size and direction; 2D method
• hydraulic tests on pre-existing fractures (HTPF)	• size and direction; 3D method
• measurement of normal stress against induced fractures	• size and direction, 2D method
• borehole break-outs, measurement with caliper	• direction of principal stresses in plane perpendicular to borehole
• mapping of core discing	• high rock stresses in borehole wall in relation to strength of rock
• focal plane analysis from seismic monitoring, local network	• stress field (direction)
Investigation of mechanical properties	
Rock-mechanical laboratory tests	**Mechanical properties**
• compression tests (uni- and multiaxial)	• deformation and strength properties
• determination of p wave velocity	• p wave velocity
• Brazilian tests	• tensile strength
• normal loading tests on fractures	• normal stiffness
• shear tests on fractures	• shear strength, shear stiffness
• core mapping	• construction properties (RMR, Q)
Other laboratory tests	**Other properties**
• thermal tests (see also thermal programme)	• coefficient of thermal expansion
• density determination	• density
• x-ran diffraction	• clay mineral determinations
Processing of geophysical data	**Interpretation basis**
• seismic measurements and sonic logging	• dynamic propagation velocity

Table B-4. Thermal methods

Method	Information
Investigation of thermal properties of rock	
Field methods	**Temperature of bedrock**
• temperature logging	• temperature distribution in groundwater and (indirectly) rock mass with depth
• thermal response test in borehole	• field determination of thermal properties of rock mass
Laboratory methods	**Thermal properties**
• determination of thermal conductivity	• thermal conductivity
• determination of specific heat capacity	• specific heat capacity
• determination of density	• density
• determination of porosity	• porosity
• determination of chemical and mineralogical composition	• chemical and mineralogical composition

Table B-5. Hydrogeological methods

Method	Information
Meteorological and hydrological methods	
Analysis of existing surface hydrological data	**General basic information, basis for boundary conditions**
• Topography, watercourses, springs	• drainage basins • recharge/discharge areas
Meteorological and surface hydrological mapping and long-term monitoring	**Interpretation basis for boundary conditions**
• Meteorology – precipitation, snow depth – temperature, evapotranspiration – air pressure	• meteorology and flows: long-term recorded parameters • for description of local climate • for modelling of groundwater recharge
• Hydrology – flows in major watercourses – springs, location and flow (if any) – recharge/discharge areas – small watercourses, location and flow (if any)	
– (mapping – Quaternary geology)	• (see geology)
Hydrogeological methods	
Investigations/documentation of wells	
Analysis of existing data for wells and facilities	**General basic information**
• Well archive etc	• hydraulic and hydrogeochemical properties of soil strata and surface rock • land use • damming undertakings, drainage etc
Data collection from existing wells and observation pipes	**Basic information in area of interest**
• Existing wells – capacity data – groundwater abstraction data	• hydraulic parameters for soil strata/surface rock (as above, but more detailed within limited area)
– groundwater levels	• basis for monitoring programme
• Observation pipes – capacity data – groundwater levels	• together with meteorological and surface water hydrological data, collected data under this point comprise an initial basis for conceptualization of groundwater recharge and modelling
Hydraulic borehole investigations	
Recording of flushing water parameters during drilling	**Interpretation basis**
• flushing pressure, flushing water content, flushing flow, return flow, drawdown, electrical conductivity	• flushing water balance • hydraulic structures
• sampling of drill cuttings	• hydraulic connections/connectivity
• recording in existing nearby boreholes	
Hydraulic tests during drilling	**Hydraulic parameters**
• pressure recording • pumping tests • (water sampling)	• natural groundwater pressure • hydraulic conductivity (K) scale ≥100m • transmissivity (T) for major hydraulic structures • (see chemistry)
Absolute pressure measurement/calculation	**Absolute pressure**
• during drilling • indirect from tests • from separate measurement • from monitoring	• natural groundwater pressure; for checking and calibration of groundwater modelling • checking of circulation in open borehole

Method	Information
Analysis of geophysical methods • temperature • liquid resistivity • point resistance • caliper	**Interpretation basis for** • hydraulic structures • groundwater density
Flow logging • **Spinner, UCM** – cumulative flow along borehole under constant drawdown – flow – temperature – liquid resistivity	**Hydraulic parameters** • hydraulic structures: location and T (estimate based on full-hole test) • frequency of major hydraulic conductors (10 m scale) • groundwater density
• **Differential flow log** – sectional inflow under constant drawdown – different section lengths and drawdowns – flow – temperature – liquid resistivity – point resistance	• K/T distribution for rock mass and hydraulic structures (local major and local minor fracture zones) • frequency of hydraulic conductors (m to dm scale) • natural groundwater pressure • groundwater density
Groundwater flow measurements • Dilution probe (SKB) – undisturbed conditions – disturbed conditions (pumping tests) • Temperature pulse method (Posiva) – undisturbed conditions – disturbed conditions (pumping tests)	**Calculation basis for** • natural groundwater flow (model calibration) • if K or T is determined by independent method, the pressure gradient can be calculated • flow response during pumping tests (understanding of hydraulic connectivity in evaluation of tests)
Hydraulic injection tests • Single closed test section, – constant pressure, optimized test times – transient recording, – different section lengths and injection pressures – (possible interference between sections)	**Hydraulic parameters** • K distribution for rock mass and hydraulic structures (local major and local minor fracture zones) (plus skin) • frequency of hydraulic conductors (> m scale) • flow magnitude • (natural groundwater pressure) • (possible connectivity)
Single-hole pumping tests • Single open test section (usually whole borehole) – constant flow, optimized test times, – transient recording (flow, drawdown, electrical conductivity) • Single packered-off test section – constant flow, optimized test times – transient recording (flow, drawdown, electrical conductivity) – different section lengths	**Hydraulic parameters** • K for rock mass or T for dominant hydraulic structure • flow magnitude • (natural groundwater pressure) • (possible connectivity)
Hydraulic interference tests • Pump holes – open or sectioned boreholes, – constant flow, – optimized test times, – transient recording (flow, drawdown, electrical conductivity)	**Hydraulic conditions and parameters** • verification of geometry and connectivity of essential structures • K for rock mass or T for hydraulic structures (local major and local minor fracture zones • flow magnitude

Method	Information
• Observation holes – open or sectioned boreholes – transient recording (drawdown, possible electrical conductivity) – flow change (optional in certain borehole sections, groundwater flow measurement by dilution method)	• (storage coefficient)
Hydrogeological monitoring	
Long-term monitoring of groundwater pressure	**Groundwater pressure variations in time and space**
• groundwater levels in open wells/boreholes in soil and surface rock • groundwater pressure in borehole sections (see also hydraulic interference tests)	• natural conditions • groundwater level map • boundary conditions for groundwater modelling • calibration and verification of groundwater models
Long-term monitoring of groundwater flow	**Groundwater flow variations in time and space**
• groundwater flow in borehole sections (see also hydraulic interference tests)	• natural conditions • calibration and verification of groundwater models

Table B-6. Hydrogeochemical methods

Method	**Information**
Hydrogeochemical methods	
Surface waters and near-surface groundwaters	
Sampling of surface waters and precipitation	**Hydrochemical overview**
• Precipitation	• According to chemical class[1] 3
• Lakes	• According to chemical class[1] 3
• Sea	• According to chemical class[1] 5
• Springs	• According to chemical class[1] 5
• Watercourses (streams, rivers, etc)	• According to chemical class[1] 3
Sampling of sediment pore waters	• According to chemical class[1] 5
Sampling of wells	• According to chemical class[1] 3
Sampling in soil pipes	• According to chemical class[1] 5
Hydrogeochemical borehole investigations	
Sampling in percussion boreholes	**Hydrogeochemical overview**
	• groundwater composition (chemical class 3)
Sampling during core drilling	**Chemical characterization of principal components**[2]
• flushing and return water samples	• for quality control
• from "telescope portion" 0–100 m	• "early" hydrochemical overview
• "in situ" sampling with packered-off section, before hydrochemical disturbance	– for sections of rock mass – for hydraulic structures
Hydrochemical logging (hose sampling)	**Chemical characterization of principal components**[2]
• "continuous" water sample of water column along open hole	• for identification of interface with saline groundwater • "early" hydrochemical overview
Sampling during pumping tests	**Extensive chemical characterization of groundwater**[3]
• in single-hole pumping tests	• for rock mass and hydraulic structures
• in interference tests in cases where $T > 10^{-6}$ m^2/s	• for essential hydraulic structures
– recording of Eh and pH on ground surface	
Complete chemical characterization with mobile field laboratory	**Complete chemical characterization of groundwater**[4]
• from borehole sections $10^{-8} < K < 10^{-6}$ m/s	• fractures and local minor fracture zones
– check of flushing water content	
– in-situ recording of Eh and pH	
– analysis in field laboratory and external laboratories	
– pressurized samples	
Hydrochemical monitoring	
Long-term monitoring of chemical parameters	**Interpretation basis**
• sampling programme	• principal components
– soil pipes, wells, boreholes	• chemical stability
– optimized measurement frequency	• indication of hydraulic disturbance
	• groundwater density
Analysis	
Water analysis acc. to chemical classes 1 to 5	• Analysis data
Fracture-filling mineral analysis	**Fracture-filling mineral characterization**
	• type
	• chemical composition
	• age/history

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[1] See Hydrogeochemical sampling and analysis, section 9.5 in /SKB, 1998/.

[2] Chemical class 3 incl. isotopes.

[3] Chemical classes 4 and 5 with Eh and pH, (possible humic-fulvic).

[4] Chemical classes 4 and 5 with Eh and pH, dissolved gases, bacteria, humic-fulvic, colloids, etc.

Table B-7. Transport methods

Method	Information
Methods for transport properties of rock	
Laboratory measurements	
Matrix diffusion measurements	• sorption coefficients • matrix diffusivity • matrix porosity
Gas diffusion measurements	• matrix diffusivity • matrix porosity
Porosity measurements	• matrix porosity
Batch sorption measurements	• sorption coefficients
Field measurements	
Resistivity measurement	• diffusivity
Radon measurement	• flow-wetted surface
Single-hole tracer tests (dilution measurement)	• groundwater flow • Darcy velocity • verification of structural model (in combination with pumping)
Single-hole tracer tests (push-pull)	• flow porosity • transport resistance • dispersivity • indication of matrix diffusion • comparative sorption data
Single-hole tracer tests(in-situ sorption)	• sorption data • diffusion data
Cross-hole tracer tests	• travel time • dispersivity • flow porosity (effective fracture aperture) • transport resistance • verification of structural model (connectivity) • comparative sorption data • indication of matrix diffusion

Table B-8. Methods for drilling

Method	Information
Drilling **Percussion drilling** • Standard percussion drilling (well drilling) • Specialized percussion drilling; for special purposes such as boreholes for hydrogeochemical sampling (e.g. ejector ODEX or reverse circulation)	Primary product: • borehole **Measurements/recordings during drilling:** • drill cuttings (rock types/alteration) • drilling rate data (fracture zones) • influx increase (hydraulic conductors)
Core drilling • SKB's version with telescope design • Core drilling with wire-line • Core drilling with pipe handling • Controlled drilling (as needed)	**Primary product:** • borehole • drill core (for geological documentation, see mapping with BOREMAP) **Measurements/recordings during and after drilling:** • drilling rate data (for interpretation of fracture zones) • flushing water parameters (for identification of hydraulic conductors, and data for flushing water balance calculations)
Soil drilling and probing	**Data for Quaternary geological interpretation:** • soil depth • soil strata sequence • possibly with sampling of surface rock Boreholes can be used as: • observation holes for groundwater table • groundwater sampling

ISSN 1404-0344

CM Digitaltryck AB, Bromma, 2001