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Framework programme for detailed characterisation in connection with construction and operation of a final repository for spent nuclear fuel

Svensk Kärnbränslehantering AB

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Preface

During the period of site investigations 2002–2007, the geoscientific and surface ecological conditions within the investigation area at Forsmark were thoroughly characterised by air-borne and surface investigations as well as by drilling to and beyond the planned depository depth. The resulting vast data material served to establish geoscientific and surface ecological models of the site. These models, which have been judged as generally robust and reliable, although with some well-defined remaining uncertainties, have been the basis for safety assessments of the Forsmark site presented in the SR-Site reports.

Investigations performed from the ground surface can, however, never achieve the detail needed to construct deposition tunnels and other underground openings or to position deposition holes adapted to local bedrock conditions at repository depth. Therefore, the previously performed investigations from the ground surface need to be supplemented with underground characterisation.

This report, which is an Appendix to SKB's application under the Nuclear Activities Act to construct and operate a final repository for spent nuclear fuel at Forsmark, presents a framework programme for detailed characterisation to be performed during the period of construction and operation. The point of departure for this programme is the presently existing site descriptive model of Forsmark, the safety assessments based on that model and the design of the repository. With this background in mind, characterisation strategies have been formulated in the report aiming at detailed adaptation of the repository layout to the variable host rock conditions. Application of these strategies will to some extent necessitate development of new methodologies and tools for investigations and modeling. Current ideas on development needs are presented in the report.

Four authors were engaged in writing the report: Assen Simeonov, SKB, who was also editor, Karl-Erik Almén, KEA GEO-Konsult AB, Lennart Ekman, LE Geokonsult AB, and Anders Winberg, Conterra AB.

Reviews of the report were made by the following reference group: Kaj Ahlbom, SKB, Johan Andersson, Streamflow AB, Rolf Christiansson, SKB, Roland Johansson, Swedpower AB, and Bengt Leijon, Conterra AB. The report has also been reviewed by Olle Olsson, SKB.

Assen Simeonov
Editor

Abstract

This report presents a programme for the detailed investigations planned to be applied during construction and operation of the repository for spent nuclear fuel at Forsmark. The report is part of SKB´s application according to the Nuclear Activities Act.

The detailed investigations shall provide relevant data on and site-descriptive models for the bedrock, soil deposits and eco-system of the site in order to facilitate a step-wise design and construction of the final repository. This shall be implemented in a manner that all demands on long-term safety are fulfilled, including accurate documentation of the construction work, and so that assessments of the environmental impact of the repository can be made. For the operational phase, the detailed investigations should also provide support to the deposition process with related decisions, thereby enabling fulfilment of the design premises for the siting and construction of deposition tunnels and deposition holes, as well as for deposition of canisters, and for the subsequent backfilling and closure of the repository.

The Observational Method will be applied during the construction of the repository. This method entails establishing in advance acceptable limits of behaviour regarding selected geoscientific parameters and preparing a plan with measures to keep the outcome within these limits. Predictions of expected rock properties are established for each tunnel section. The outcome after excavation is compared with the acceptable range of outcomes. Information from detailed characterization will be of essential importance for application of the Observational Method and for adapting the repository to the prevailing rock properties.

SKB has for the past several decades developed methods for site characterisation, applying both above- and underground investigation techniques. Experiences from this work, put into practice during the site investigations, has resulted in a solid knowledge and understanding of the bedrock conditions at Forsmark. The detailed investigations will employ, apart from established and earlier practiced methods, also further refined and newly developed techniques and methods for investigations and modelling. The report describes the present status for investigation and modelling methodology and techniques and also provides an overview of currently planned method developments.

The report also presents a proposed scenario for how the detailed investigations, in light of presently available knowledge and techniques, should be conducted. Starting points for the investigation programme in this context are the reference design of the facility and remaining uncertainties associated with the site descriptive model and underground design. The scenario high-lights those investigations which, more or less as a matter of routine work, will be performed closely coordinated with the progression of the underground excavation work. The investigations related to the development of the deposition areas will primarily be linked to the sequences pilot drilling followed by excavation of deposition tunnels, and pilot drilling with subsequent full-face drilling of deposition holes. Continuous supervision of the fulfilment of design premises and documentation of the facility are in this context important issues.

Information acquired during the construction process will also provide the substantial basis for the assessment of the long-term safety of the final repository. Further, it is emphasised in the report that supplementary investigations will be performed, if the information in any respect is regarded as insufficient. Such investigations may as well be performed from the ground surface. The final repository will in different ways have an impact on the surrounding environment. Monitoring of such changes is therefore an important and integral part of the detailed investigations.

Until the construction work for the final repository is initiated, the detailed investigation programme will be modified and made more circumstantial, including results of planned developments. These updates will be accounted for in ensuing versions of the programme.

Sammanfattning

Denna rapport presenterar ett ramprogram för detaljundersökningar under uppförande och drift av slutförvaret för använt kärnbränsle i Forsmark. Rapporten utgör underlag för SKB:s ansökan enligt kärntekniklagen.

Detaljundersökningarna ska ge relevanta data om och platsbeskrivande modeller för platsens berggrund, jordlager och ekosystem så att det är möjligt att steg för steg projektera och bygga slutförvaret. Detta ska ske på ett sådant sätt att säkerhetskraven uppfylls, den byggda anläggningen blir noggrant dokumenterad, och så att bidrag till bedömning av miljöpåverkan tillhandahålls. För driftskedet ska detaljundersökningarna ge stöd för deponeringsprocessen och dess beslut, så att uppställda krav (konstruktionsförutsättningar) för placering och utförande av deponeringstunnlar och deponeringshål, för deponering av kapslar samt för återfyllning och förslutning av förvaret uppfylls. De konstruktionsförutsättningar som påverkar detaljundersökningsprogrammet beskrivs i en bilaga till rapporten.

Vid uppförandet av slutförvaret kommer observationsmetoden att tillämpas. Metoden innebär att man i förväg definierar acceptabla utfallsrum för olika geovetenskapliga parametrar och upprättar en plan med åtgärder för att hålla utfallet inom angivna gränser. För varje tunnelavsnitt upprättas prognoser av förväntade bergegenskaper. Utfallet efter utbrytning jämförs sedan med det acceptabla utfallsrummet. Information från detaljundersökningarna kommer att ha väsentlig betydelse vid tillämpning av observationsmetoden och för att anpassa slutförvaret till berggrundens egenskaper.

SKB har under flera årtionden utvecklat metoder för platskaraktärisering av berggrunden med hjälp av undersökningar både från markytan och under jord. Erfarenheterna från detta arbete tillämpades vid platsundersökningarna, vilket resulterade i en god kunskap om och förståelse av berggrundsförhållandena i Forsmark. Vid detaljundersökningarna kommer, förutom etablerade och tidigare tillämpade metoder, även vidareutvecklade och nya metoder för undersökningar och modellering att användas. Förutom nuläget av metodik och teknik för undersökningar och modellering beskriver rapporten även de utvecklingsinsatser som för närvarande planeras.

Rapporten redovisar också hur detaljundersökningarna, mot bakgrund av nuvarande kunskap och teknikstatus, föreslås bli utförda. Utgångspunkter för programmet är dels anläggningens referensutformning och de frågeställningar som aktualiserats mot bakgrund av konstruktionsförutsättningarna för respektive anläggningsdel, dels kvarstående osäkerheter i den platsbeskrivande modellen och för anläggningsutformningen. Programmet lyfter fram de undersökningar och modelleringar som mer eller mindre rutinmässigt kommer att genomföras samordnat med bergarbetenas framdrift. Vid utbyggnad av deponeringsområdena är sekvenserna pilotborrning, undersökningar och byggande av deponeringstunnlar samt pilotborrning, undersökningar och utförande av deponeringshål centrala aktiviteter. Kontinuerlig kontroll av att konstruktionsförutsättningarna uppfylls, liksom detaljerad dokumentation av anläggningen, är härvid viktiga verksamheter.

Den information som insamlas under uppförandet utgör också underlag för förnyad bedömning av slutförvarets långsiktiga säkerhet. I rapporten betonas att kompletterande undersökningar kommer att genomföras om informationen inom något område bedöms vara bristfällig. Sådana undersökningar kan även komma att utföras från markytan. Slutförvarsanläggningen kommer att på olika sätt påverka platsen och dess omgivning. Monitering av förändringar är därför viktigt och utgör en integrerad del av detaljundersökningsprogrammet.

Fram till dess att bygget av slutförvaret inleds kommer detaljundersökningsprogrammet att modifieras och detaljeras, bland annat med hänsyn till resultat från SR-Site samt utvecklingen av undersökningsmetoder och instrument. Dessa uppdateringar kommer att redovisas i kommande versioner av programmet.

Contents

1 Detailed characterisation – background and purpose

1.1 Background

This report presents a programme for detailed characterisation during construction and operation of the repository for spent nuclear fuel at Forsmark. The report comprises background material for SKB's application under the Nuclear Activities Act. The focus of attention is on the repository's long-term (post-closure) safety, which governs the requirements for both investigations and execution. The report supports and supplements SKB's report "Design, construction and initial state of the underground openings", hereinafter referred to as the Design and Construction Report /SKB 2010a/).

SKB already has good knowledge of the bedrock conditions at Forsmark today. The site description for Forsmark /SKB 2008a/ gives an account of the properties of the site and comprises a synthesis of a large number of underlying reports that describe the entire chain from data collection to finished site descriptive model. The site engineering report /SKB 2009a/ presents an interpretation of the site descriptive model as a basis for the site-adapted design of a final repository at Forsmark. The remaining uncertainties in the site description are summarised in /SKB 2008b/. Based on this material, a site-adapted layout of the underground parts of the final repository has been prepared /SKB 2009b/.

Investigations, analysis and modelling during the construction and operation of the final repository will be carried out to provide a basis for final adaptation to prevailing rock conditions. This requires a higher level of detail in measurements, analysis and modelling of investigation data than was the case with the completed site investigation. Future investigations, analyses and modelling will therefore be referred to as "detailed characterisation", and the entire programme is designated "the detailed characterisation programme".

Over the years SKB has accumulated knowledge of methods for characterisation of the bedrock. The foundation was laid during the study site investigations of the '70s and '80s and the geoscientific research and development that was conducted within the Stripa Project, followed by preliminary investigations for the Äspö HRL. The investigations conducted in connection with the construction of the Äspö HRL and subsequent research activities have contributed further knowledge concerning methods and instruments for underground characterisation. Collaborative international efforts have contributed experience from other organisations, among which SKB's Finnish sister organisation Posiva occupies a special position. Finland's final repository concept is the same as that of Sweden, and cooperation with Posiva on detailed characterisation will be pursued both at their research facility ONKALO and at the Äspö HRL.

The detailed characterisation programme will be developed and elaborated up until the time of its execution. In the ensuing years up to the start of construction, the programme will need to be updated in the light of the results of the Safety Assessment Reports, particularly the report "Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project" (hereinafter called SR-Site /SKB 2011/), the regulatory review of this report and whatever conditions may be linked to the licence to build and operate the final repository. Further, methods and instruments for detailed characterisation will be refined and tested, see also RD&D programme 2010 /SKB 2010b/. The process of developing the programme so that it will be available for various phases in the construction and operation of the final repository is described below.

1.2 Purpose and scope of the report

The purpose of this report, which is the first version of the detailed characterisation programme, can be expressed in the following points:

- To present the overall premises and strategies for the detailed characterisation programme.
- To give examples of how the programme can be applied during construction and operation of the final repository in observance of requirements on long-term safety.
- To present SKB's plans for continued evolution of programme, methods and tools for investigations, modelling, data handling and quality assurance.

Since the detailed characterisation lies several years ahead in time, the development work is planned to be carried out in steps. The term "framework programme" in the title of the report refers to the fact that the report will provide a general description of the investigations that are planned for the repository's entire construction and operating period. It is difficult to predict in detail all the requirements that will be made on the investigations over such a long period of time, as well as what opportunities new technology will offer. The detailed characterisation programme must therefore be described primarily in general terms for the time being. Detailed programmes for different parts of the facility (accesses, central area and repository area) will be presented later in separate reports. Figure 1-1 provides an overall picture of the process for the development of the detailed characterisation programme.

The detailed characterisation programme does not address questions concerning construction control, working environment or investigations specifically intended for environmental control. By "environmental control" is meant activities aimed at preventing the impact of the final repository on the natural environment, as well as monitoring of possible environmental impact. Environmental control will utilise data from detailed characterisation, such as data showing how the facility affects the groundwater situation. A proposal for an environmental control programme aimed at environmental impact including noise and vibration is presented in "Förslag till kontrollprogram. Uppförande och drift av anläggningar för mellanlagring, inkapsling och slutförvaring av använt kärnbränsle" ("Proposal for control programme. Construction and operation of facilities for interim storage, encapsulation and final disposal of spent nuclear fuel"), which comprises an appendix to the application under the Environmental Code.

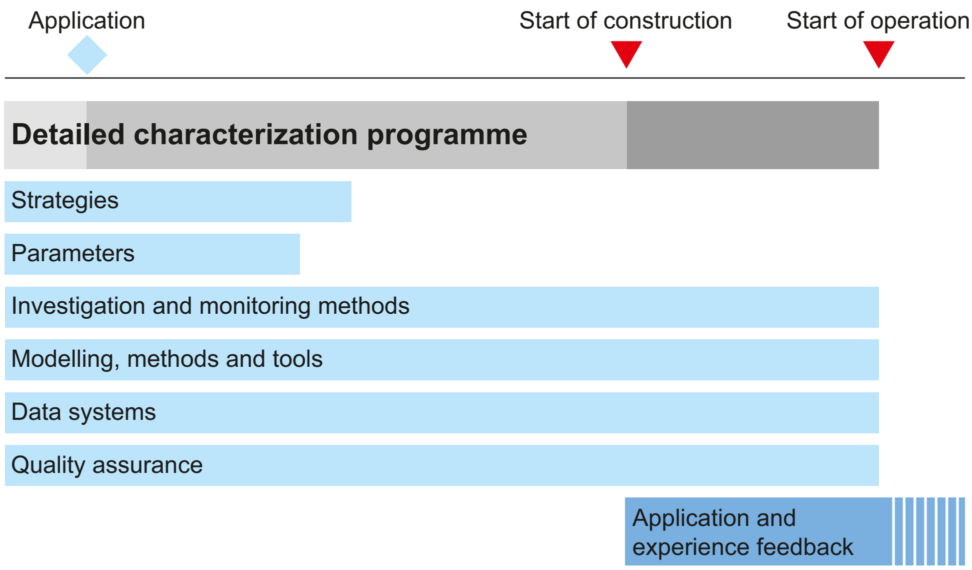


Figure 1-1. *The detailed characterisation programme with associated background material will be further refined with updated reports, for example prior to start of construction and start of operation.*

1.3 Purpose and execution of detailed characterisation

The purposes of detailed characterisation are:

- To provide a basis for adaptation of the repository to the site-specific conditions in order to meet the design premises, e.g. with respect to long-term safety.
- To provide a basis for engineering-related decisions concerning e.g. grouting and rock support measures.
- To update site descriptive models, which will in turn serve as a basis for long-term safety assessments.

The detailed characterisation should furnish relevant and adequate information on the bedrock, soil layers and ecosystems of the site to permit step-by-step design and construction of the final repository in such a way that the safety requirements are fulfilled, to document the built facility and to contribute to an assessment of environmental impact. This means that the generally favourable properties of the site (low fracture frequency as well as low hydraulic transmissivity at repository depth, generally high thermal conductivity and a suitable hydrogeochemical environment) should be verified and that the layout and placement of deposition holes should be adapted to the properties of the bedrock. Adaptation of the layout may, for example, entail optimising the orientation of the deposition tunnels in relation to the rock stresses and adjusting the distance between deposition holes with respect to the thermal conductivity of the rock.

For the operating phase, the first purpose entails gathering data and constructing detailed models in support of the deposition process so that the design premises are fulfilled for placement of deposition tunnels and deposition holes, deposition of canisters as well as backfilling and closure. The third purpose, regarding modelling, entails that information from detailed characterisation should be used for step-wise updating of the site description by increasing the degree of detail of the models and reducing their uncertainties.

Modelling should be carried out within different geoscientific disciplines with the requisite determinism and on a relevant modelling scale. Modelling strategy and methodology should be further developed based on experience from the site investigations and communicated in subsequent programme versions. Furthermore, a "tool box" of methods, instruments and computer systems for investigation, modelling, data processing and data storage should be available and be documented. Requirement fulfilment should be checked regularly and improvements adopted as needed.

Detailed characterisation should be closely coordinated with design and construction, where application of the Observational Method (see Section 1.4.4) is the overall strategy for collection and use of information. SKB's application of the Observational Method for the final repository will be continuously refined up to the start of construction.

Detailed characterisation will be quality-assured with respect to execution and results. Quality assurance is based on experience from the site investigation and will be further developed with a view to the requirements that will be made on the final repository and the integrated work forms that will be employed. Quality aspects are dealt with more thoroughly in Chapter 5.

1.4 Construction and operation of the final repository

The way in which layout of the final repository is to be adapted to the properties of the site has been determined within the design process. The reports that can be mentioned here are the facility description for Forsmark /SKB 2010c/ and the underground design report /SKB 2009b/. The latter presents a layout that is adapted to the properties of the bedrock, methods for construction and an analysis of execution risks. The Design and Construction Report /SKB 2010a/ describes the chosen reference design and methods for rock excavation, sealing and rock support and shows how this leads to fulfilment of the design premises for long-term safety. The design premises are presented in /SKB 2009c/.

1.4.1 Phases

The process of building the final repository and depositing spent nuclear fuel will take several decades, see Figure 1-2. A hard rock facility of considerable size will have been completed when the last copper canister has been deposited.

The construction phase commences when SKB has obtained a licence to build the final repository and construction has begun. During this phase the accesses to the final repository and the central area will be built, along with underground openings and installations that are needed for the activities during the operating phase. The first deposition tunnels will be driven during the latter part of the construction phase, and a number of deposition holes will be drilled to permit fine-tuning of the deposition technology. Even though technical systems will be commissioned during the entire construction phase, this activity will gradually increase towards the end of the phase. During *commissioning*, facility documentation will be prepared and an operating organisation will be assembled. Integrated testing of the entire final repository system will also be performed then. Based on this, an updated *Safety Assessment Report* (SAR) will be prepared as a basis for an application for a licence to begin deposition of spent nuclear fuel.

When a licence for deposition has been obtained, the *operating phase* commences. After a period of trial operation, routine operation begins, during which safe and functional work procedures are fundamental. The operating phase includes continued expansion of the repository area, at the same time as deposition is carried out in the already built parts. Operation consists of excavating underground openings for deposition (tunnels and deposition holes), depositing canisters of spent fuel, sealing deposition holes and backfilling tunnels (closure). It is thus the operating phase that comprises the dominant part of the activity in both time and space. More than 6,000 canisters will be deposited during a period of more than 40 years.

1.4.2 Main processes in construction and operation of the final repository

According to "Verksamhet, ledning och styrning – uppförande av slutförvarsanläggningen" ("Activities, management and steering – construction of the final repository", hereinafter referred to as Appendix VU /SKBdoc 1199888/), the rock-related activities during the final repository's construction phase can, on a general level, be divided into two main processes:

- Construction.
- Safety assessment.

The relationship between the two main processes is illustrated in Figure 1-3. During the operation phase the deposition process will be integrated with the construction process, as illustrated by the dashed box in the figure.

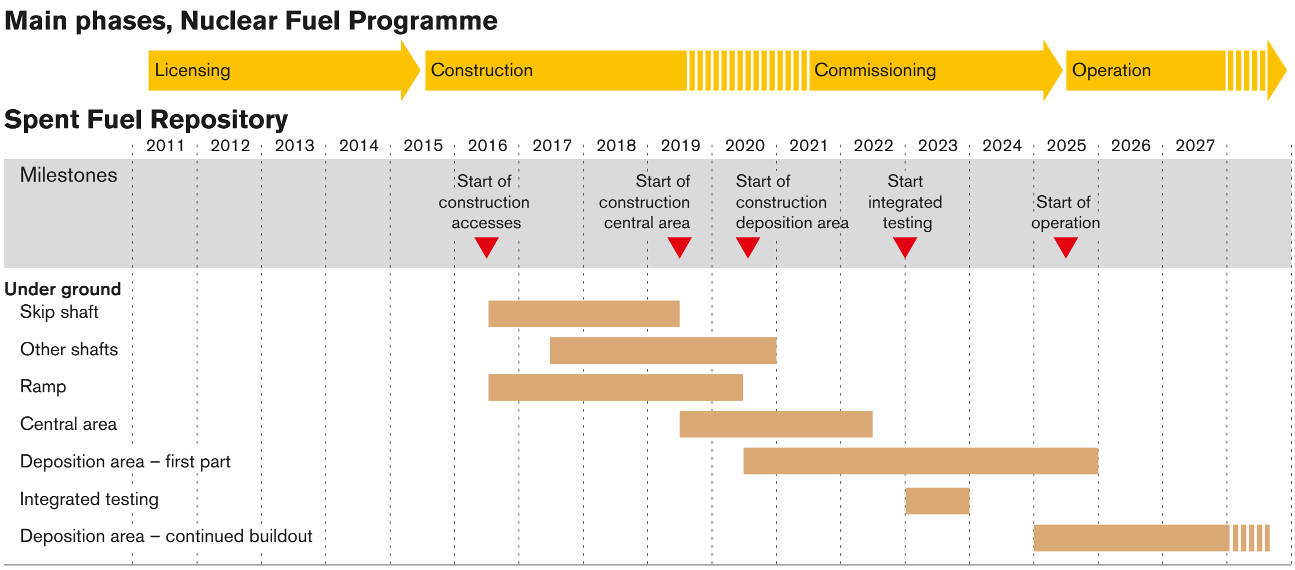


Figure 1-2. *Overall timetable for the underground facilities of the final repository.*

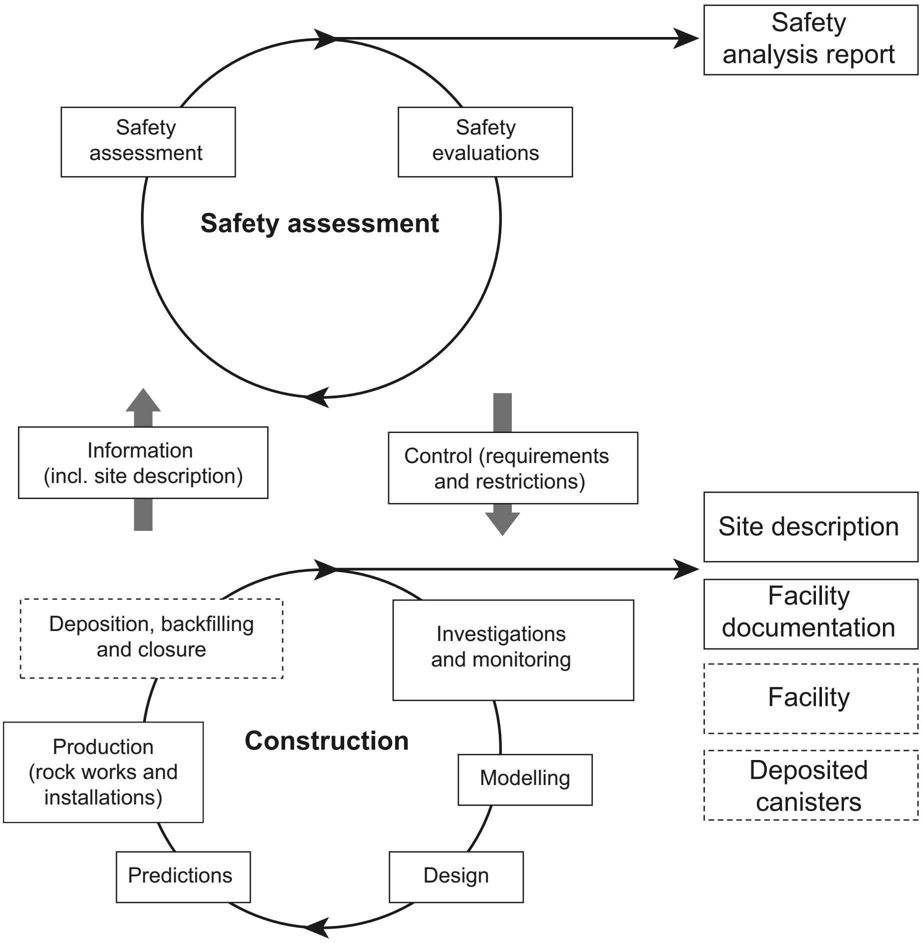


Figure 1-3. *Illustration of the main processes of the construction phase, Construction and Safety Assessment. Dashed components are added when the final repository is put into operation.*

The goal of the main process *Construction* is to deliver accesses, a finished central area and excavation for trial operation. The activities include investigations, modelling, design, rock works as well as design and installation of technical systems.

Design, investigations and construction (production) require well-functioning coordination and exchange of information, since the investigations will be conducted in parallel with ongoing production. An essential purpose of investigations and modelling is to regularly update the basis for design and construction of the different repository parts. Updating of the site descriptive model of the entire repository area and areas beyond it is done less frequently and primarily for the main process *Safety Assessment.*

The main process *Safety Assessment* includes activities aimed at updating the *Preliminary Safety Assessment Report* (PSAR) to a Safety Assessment Report (SAR), which comprises a part of the application for a licence to commence trial operation. Safety Assessment also provides steering for the main process *Construction* so that the final repository fulfils the safety requirements (Appendix VU, /SKBdoc 1199888/). The safety issues, which can concern both operational (pre-closure) safety and long-term (post-closure) safety and which comprise a central part of execution, concern in this context those issues that relate to the properties of the site and the function of the engineered barriers.

Within the main process Safety Assessment, regular cross-checks are made against updated site descriptive models and against premises and assumptions in the most recent Safety Assessment Report. The work is based on the site description produced following completed site investigations /SKB 2008a/ and the Safety Assessment Reports, SR-Site and PSAR, submitted along with the application and prior to the start of construction.

Unforeseen events can occur during execution; some may have a bearing on safety. A function called Safety In Project (SIP) is included to ensure uniform documentation and management of these events. The goal of SIP is that it should exercise continuous monitoring of geoscientific conditions that affect site adaptation, underground work and deposition work (including monitoring and inspection of stray materials). By means of SIP, events that can affect quality-critical elements in the project can be detected and dealt with at an early stage (Appendix VU, /SKBdoc 1199888/).

1.4.3 Strategy for design and construction

Building in rock is associated with uncertainties, which must be managed in connection with design and construction. Even if an extensive site investigation has been carried out and the resulting models describe the properties of the rock in relatively good detail, because of spatial variability and uncertainties for certain properties, it is not possible to completely determine the layout of the facility and strategies for construction at the start of the construction work. Layout and site-specific design solutions will instead be progressively adapted to the rock in increasing detail as new investigation results and construction experience become available and new models are developed. The design premises regarding long-term safety are in the focus of this process.

In order to specify the requirements on the execution and function of the final repository and visualise the planned production flow up to a finished repository, SKB has defined a number of production lines, of which the Design and Construction Report includes construction and excavation of the underground parts of the final repository. The Design and Construction Report /SKB 2010a/ describes the chosen reference design and methods for excavation, sealing and support of the rock and evaluates this in relation to the design premises established for the facility's long-term safety /SKB 2009c/ (the design premises are presented in Appendix 1). Furthermore, the chosen reference design of canister, buffer, backfill and closure imposes further requirements on the rock. This is also explained in the Design and Construction Report. In accordance with the methodology for formulation of the design premises, they will be revised following each Safety Assessment Report.

The Design and Construction Report also describes the design methodology and technology for construction as well as procedures for verifying that the safety requirements for the final repository are fulfilled. The detailed characterisation programme will play a significant role in this by providing data to serve as a basis for both adaptation and verification of requirement fulfilment, see Section 2.2. Planned technology for the construction and operation of the final repository is presented in the Design and Construction Report as "reference methods", by which is meant the methods that will be used in keeping with the applicable premises. If the design premises are revised or existing technology is improved, the reference methods may also eventually have to be modified or replaced.

1.4.4 The Observational Method

Underground design and rock works will be executed in accordance with the Observational Method /EN 1997-1:2004/. The method is a risk management method based on the determination of possible and acceptable behaviour of the structure prior to the start of construction. This assumes that predictions have been made of the expected properties of the rock, where a certain range of outcomes (range of variation) is judged acceptable. The properties that are primarily aimed at in the case of a hard rock facility are stability, tightness and durability. A plan of observation (measurement) will be prepared, along with a plan of contingency actions if the values risk falling outside the range of what can be accepted, i.e. outside the stipulated range of outcomes. If planned actions are not sufficient, an analysis is made of the consequences of the deviation. This may necessitate redesign and revision of construction plans (see explanation and application of SIP in Section 1.4.2).

Based on the fundamental requirements on the stability, tightness and durability of the final repository, SKB intends to further develop the Observational Method so that it also satisfies SKB's special needs for ensuring that the repository is site-adapted with respect to the design premises, including requirements concerning long-term safety and performance requirements related to other barriers, mainly buffer and backfill, see /SKB 2009c/.

Detailed characterisation and prediction of rock conditions are central activities in the application of the Observational Method to the final repository. Against this background, planning and execution of detailed characterisation is an important ongoing process for timely provision of sufficient knowledge on site conditions that can serve as a basis for modifying the detailed design of the repository.

1.4.5 Step-wise construction

The underground facility will consist of three main parts with slightly differing performance requirements, see Figure 1-4:

- Accesses (ramp and shafts).
- Central area.
- Repository area with deposition areas (main tunnels, transport tunnels and deposition tunnels).

Design of the final repository will proceed in two steps, first *system design* and subsequently *detailed design*. Buildout will proceed in stages.

As a basis for SR-Site /SKB 2011/ and the applications under the Nuclear Activities Act and the Environmental Code, the entire final repository has been designed to a uniform level called Layout D2 /SKB 2009b/. Prior to the start of construction, a review will be made of Layout D2 and constituent systems in a system design of the entire facility. Subsequently, different parts of the facility will be in different phases of planning and production with ongoing or finished deposition in certain parts of the final repository and rock works in other parts. At the same time, investigations and detailed planning may be under way for additional deposition areas.

The knowledge needs regarding the bedrock for the different facility parts as described above are somewhat different, which is of importance for detailed characterisation. For example, during the operating phase, excavation of deposition tunnels and drilling of deposition holes are important activities. Particularly in connection with decisions during the deposition process, for example regarding the route of deposition tunnels and the location and approval of deposition holes for canister deposition, detailed characterisation provides essential information. The varying information needs in different parts of the final repository are examined in greater detail in Chapter 4.

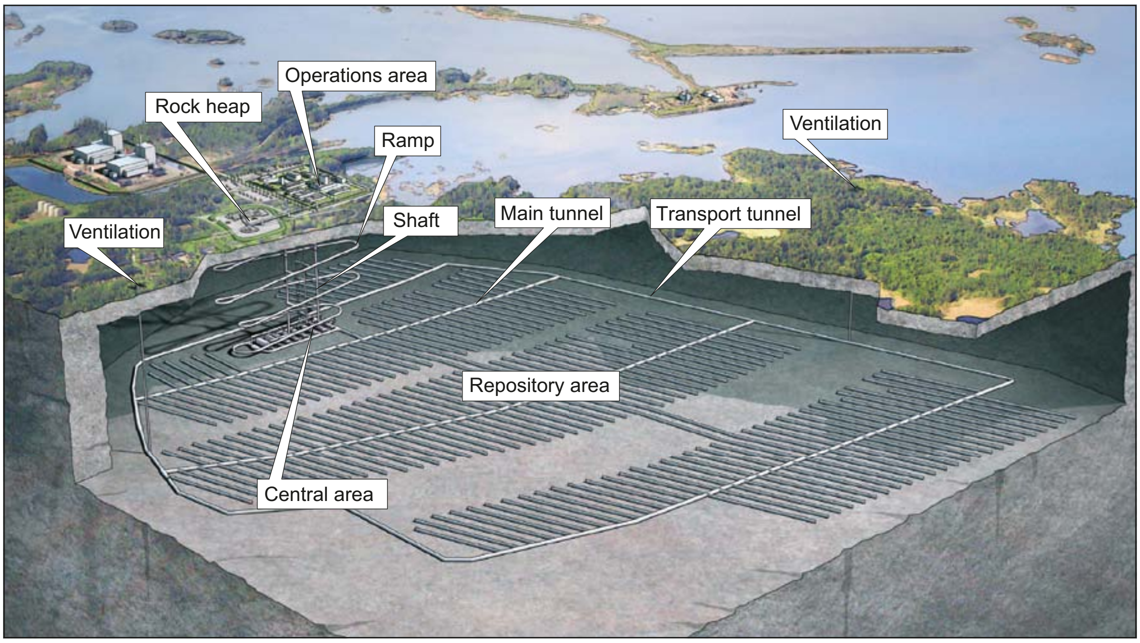


***Figure 1-4.** The final repository at Forsmark, proposed layout.*

2 Need and flow of information

2.1 Information need

Even though a relatively good idea exists of what information is required during construction and operation of the final repository, the information need from detailed characterisation has to be specified in the continued programme work, mainly with a view to:

- Fulfilment of design premises for the final repository.
- Reduction of uncertainties.

2.1.1 Information need for fulfilment design premises

The long-term safety of the final repository is dependent on arriving at the right layout of the repository in its entirety, as well as in its details, and adapting this layout to the properties of the rock. Based on the SR-Can safety assessment, SKB has stressed a number of design premises relating to the long-term safety of the repository /SKB 2009c/. The design premises consist of direct or indirect requirements on the size of the facility, how the facility is to be adapted to the properties of the bedrock, and how the construction process is allowed to affect the surrounding rock, all with the aim of ensuring long-term safety. By direct requirements is meant design premises that relate to the inherent barrier function of the rock. By indirect requirements is meant design premises intended to ensure that the design premises for other barriers (mainly buffer and backfill) can be fulfilled. In addition to these long-term safety requirements, requirements are made on the technical function of the facility during its operating time, as is evident from the Design and Construction Report /SKB 2010a/.

The design premises with a bearing on detailed characterisation are presented in Appendix 1. The role of detailed characterisation in fulfilling the design premises is also described there. A selection of the design premises that influence the design of the detailed characterisation programme is presented below, grouped according to the above categories:

Design premises regarding the barrier function of the rock (taken from /SKB 2009c/)

- The deposition holes must be located more than 100 m from deformation zones with a trace length at the ground surface of more than 3 km.
- Deposition holes should, as far as reasonably possible, be selected such that they do not have potential for shear greater than the canister can withstand ("large fractures" should be avoided, see further on in this section).
- The composition of the groundwater in rock volumes selected for deposition holes should meet the criteria established in SR-Can prior to blasting.
- The buffer geometry (e.g. void spaces), the buffer's water content and distances between deposition holes should be selected such that the temperature in the buffer is <100°C.
- The total volume of water flowing into a deposition hole from the time when the buffer is exposed to inflowing water until saturation should be limited.
- Before canister emplacement, the connected effective transmissivity, integrated along the full length of the deposition hole and averaged around the hole, must be less than 10^{-10} m^2/s.
- Excavation damage should be limited and may not result in a connected effective transmissivity, along a significant portion (at least 20–30 m) of the deposition tunnel and averaged over the tunnel floor, higher than 10^{-8} m^2/s.
- Under the top seal (the portion of the accesses located above the parts to be sealed with clay, according to the reference design), the integrated effective connected hydraulic conductivity in the backfill in tunnels, ramps and shafts and in the excavation-damaged zone (EDZ) surrounding them must be less than 10^{-8} m/s (the EDZ is explained in Section 4.5.2).

Design premises regarding underground openings and bedrock in order for the design premises for other barriers to be fulfilled, the Design and Construction Report /SKB 2010a/

- Requirements on deposition holes in terms of volume, diameter, straightness, etc in order for the buffer to fulfil its given barrier function.
- Requirements on deposition tunnels in terms of volume, cross-sectional areas and breakout in order for the backfill to fulfil its given function.
- Requirements on deposition tunnels in terms of maximum total inflow and maximum point inflow in order for the backfill to fulfil its given function.

Design premises regarding underground openings and bedrock for the facility's technical function during its construction and operating time, the Design and Construction Report /SKB 2010a/

- Requirements on maximum water inflows to the parts of the facility that are not deposition tunnels.

Fulfilment of the design premises is ensured by the use of methods specially designed for the construction and operation of the final repository (reference methods) and by quality control to make sure that execution complies with the reference methods' specifications. Detailed characterisation contributes in two ways to fulfilment of the design premises. Firstly, collected data and updated models provide a basis for design and construction, and secondly, investigation results can subsequently verify that the design premises have been fulfilled. The relationship between stipulated safety requirements, design premises, reference methods and execution and verification that the safety requirements are fulfilled is illustrated schematically in Figure 2-1.

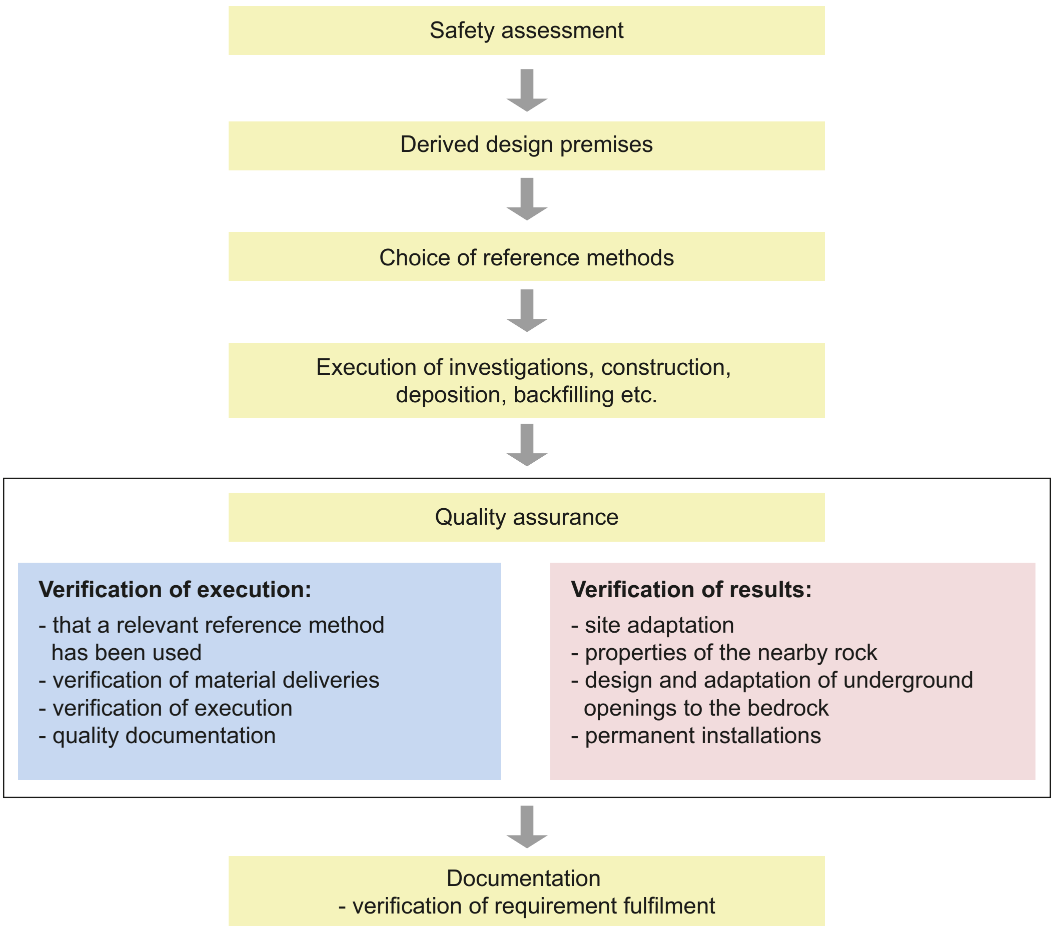


Figure 2-1. *Strategy for steering and verification of construction so that requirements on long-term safety are fulfilled. Detailed characterisation contributes by verifying the execution results, e.g. in the form of facility geometries or properties of the nearby rock.*

Examples of *directly* measurable design premises are the geometric configuration of a deposition tunnel or a deposition hole and water inflows to tunnel sections. Other design premises are, on the other hand, *not directly measurable*, such as the requirement that a deposition position may not be intersected by a "large fracture". By "large fracture" is meant a fracture or deformation zone of such an extent that it could, in connection with seismic events, cause shear so that the canister is damaged. In such cases, the design premise must instead be handled by establishing an acceptance criterion and using a specially adapted methodology for investigations and modelling. For the example of a "large fracture", the design premise has for the present been assigned the criterion EFPC *(Extended Full Perimeter Criterion)*. This criterion consists of two parts, one of which (FPC) entails that a canister position must not be intersected by a fracture or a deformation zone that can be followed around the full tunnel perimeter. Such a fracture or deformation zone is termed FPI = *Full Perimeter Intersection*. EFPC entails in addition that if one and the same fracture or deformation zone intersects five or more canister positions, they must be rejected /Munier 2010/, see Figure 2-2. Chapter 4 discusses how "large fractures", with or without the EFPC criterion, can be identified and characterised by various types of investigations and modelling in several steps. The Design and Construction Report /SKB 2010a/ describes how a chosen reference design for the final repository and methods for rock excavation are expected to fulfil the design premises for long-term safety.

2.1.2 Information need for reducing uncertainties

The SR-Can safety assessment /SKB 2006/, which was based on relatively limited information from the initial site investigation, showed that only certain site-specific properties are of essential importance for long-term safety. The assessment provided guidance on what issues may require further attention. The site descriptive model for Forsmark that was set up after complete site investigation contains a number of uncertainties. These uncertainties have been compiled in /SKB 2008b/, and their safety-related consequences are presented in the SR-Site safety assessment /SKB 2011/. SR-Site thereby serves as an updated basis for which issues require attention when the detailed characterisation programme is prepared.

The importance of the site descriptive model uncertainties for construction feasibility was evaluated in /SKB 2009b/ by means of risk assessment methods. The assessment was that none of the uncertainties that have been identified will render Forsmark unsuitable as a final repository site. In the case of several parameters, however, it was found that reduced uncertainties during the next design step or during construction would provide greater flexibility for the layout of the repository.

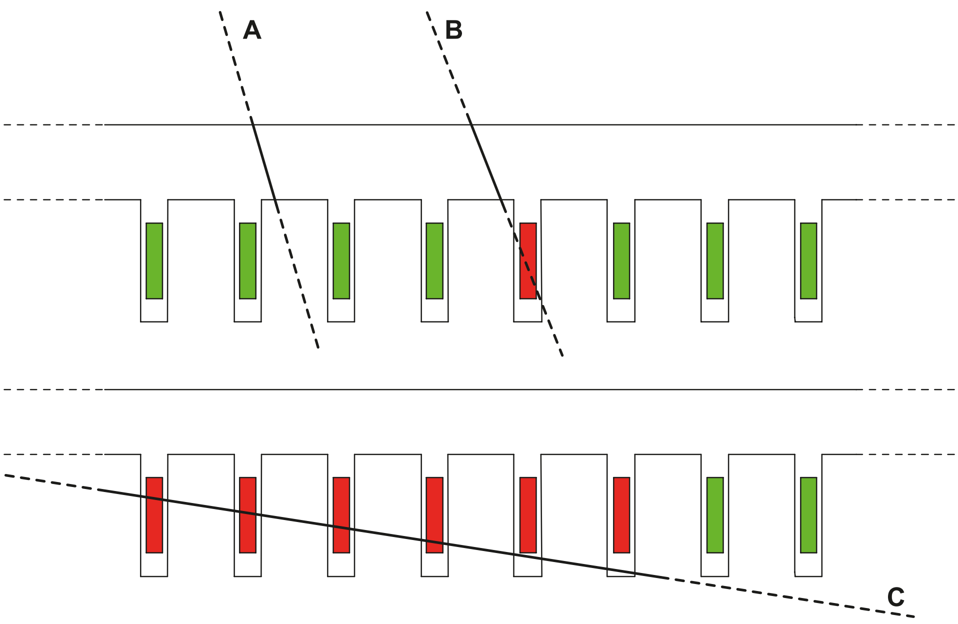


Figure 2-2. *Illustration of the implications of the EFPC criterion. A and B are two FPI objects, of which A does not affect deposition, whereas B prevents deposition. C intersects at least five deposition holes, which means that they may not be used for deposition.*

The most important parameters in this category are:

- The frequency and distribution of open water-bearing fractures and their potential influence on groundwater lowering (drawdown) in the vicinity of the shaft and ramp.
- In situ stress magnitudes and orientations at repository level.
- Spatial distribution of deformation zones that can impact the repository layout.
- Spatial distribution of amphibolite lenses with lower thermal conductivity that can be of importance for the distance between deposition holes.

The detailed characterisation programme proposed in Chapter 4 first presents the questions that are of essential importance for each facility part. These questions are based on the design premises (Appendix 1) and on the uncertainties /SKB 2009b/. It then describes how detailed characterisation can be carried out in order to answer these questions and thereby provide a relevant body of data as a basis for construction and safety assessment.

2.2 Information flow

The fundamental information flow for data from the investigations is illustrated in Figure 2-3. The results of detailed characterisation in the form of data and models is used as a basis for planning of a facility part or construction step. If necessary, supplementary information is requested so that decisions can be made regarding the current expansion of the repository on the basis of a complete body of data.

During execution of a buildout step, for example driving of one or more tunnels, the information flow is designed with a view to the fact that the information will be used for the final adaptation of the underground opening in question. Decisions made in the process are based on criteria established in connection with the design of the facility. The process is illustrated by the lower circles in

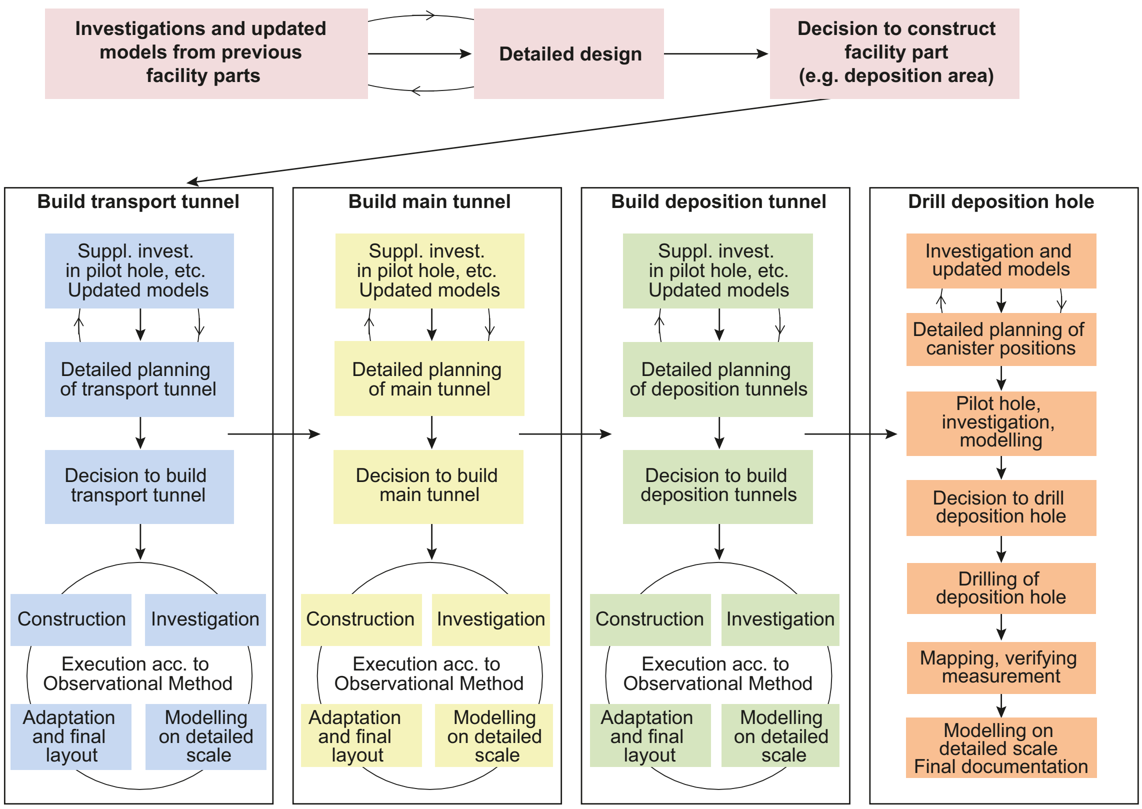


Figure 2-3. *Schematic illustration of information flow and relationships between detailed characterisation and design/planning, decision and construction. The example concerns the construction of a deposition area.*

Figure 2-3. Mapping of rock surfaces in the most recently excavated tunnel section and investigations of the bedrock in front of the tunnel face will then generate a progressively updated, detailed model to verify that production (rock excavation, rock support and installations) remains within the given range of outcomes (see Section 1.4.3). Strict logistics is important in this execution process, where the work schedule should include lead times for each task (including quality inspection and database management). Integrated planning for all actors is done so that the necessary efficiency is achieved and results of the right quality are obtained. Figure 2-3 exemplifies decisions and the flow of information linked to the decisions in connection with the construction of a new deposition area.

Regarding the flow of investigation data towards safety assessment, it is not relevant to highlight any specifically designed information flow. All site data and modelling results are saved in databases and comprise, together with other documentation on the facility, a basis for the safety assessments.

3 Methods for investigations and modelling

3.1 Overview

This chapter provides an overview of the methods which SKB plans to use for investigations and modelling of bedrock and surrounding land in conjunction with construction and operation of the final repository.

Both the programme and methods will be further refined during the years up until the start of construction. Certain methods are not needed until construction of the deposition areas, providing additional time for development.

As a result of previous site investigations, SKB has good knowledge today of geoscientific investigation methodology and models. This chapter mainly describes the experience gained from research activities at the Äspö HRL and the site investigations at Forsmark and Laxemar. Knowledge and experience concerning investigations in conjunction with the construction of an underground rock facility were accumulated during the construction phase of the Äspö HRL /Almén and Stenberg 2005/, while the modelling methodology in particular underwent considerable development during the site investigation phase /SKB 2008a, 2009d/. An essential difference regarding modelling methodology during construction and operation of the final repository compared with the site investigations is that the modelling will mainly be based on information from underground investigations distinguished by a progressively increasing degree of determinism.

A number of methods for investigations and modelling will be applied within the detailed characterisation programme, and many types of instruments and systems for measurements, data handling, data storage and modelling will be in use. In order for the project to be as well-equipped as possible for detailed characterisation, the following activities are planned for the period up until the start of construction:

1. The modelling methodology will be established, see Section 3.2 and Appendix 2. Furthermore, the information need for the construction of the final repository will be specified and systematically compiled. The modelling strategy and the information need lay the foundation for the choice of methods and instruments.
2. Methods and measurement instruments for investigations will be determined, see Section 3.3 and Appendix 3. Proven methods and measurement instruments will be evaluated relative to the background of the requirements on detailed characterisation, and the methods and instruments judged to have potential for further use in the final repository project will be selected. Where previous experience indicates a development need, methods and measurement instruments will be further developed, see Section 7.3.
3. All investigation data (quality-assured primary data) will be stored in a central SKB database, see Section 3.4. All processing, interpretations and analyses will be based on these primary data, regardless of the purpose of the investigations and of who is the information user. Similarly, processed data and interpretation results in the form of models will be stored in a model database.
4. Experience of investigation methods will be acquired from underground projects within and outside of SKB. In this context, Posiva's ONKALO facility at Olkiluoto /Posiva 2003, 2009/ is of particular importance, since it will provide access to the final repository planned by Posiva.

3.2 Modelling strategy

A general description of overall modelling strategies and model application during construction and operation is provided in this section. A brief account of current status, complementary data foreseen from construction and operation, and essential modelling tasks are provided in Appendix 2 under discipline-specific headings.

Models are utilised both in the ongoing design and construction process and less frequently in recurrent complete site descriptive modelling in conjunction with safety assessments. The need to update certain models and make predictions of the properties of the given rock volume is clarified in the planning work prior to each major construction step. In accordance with the principles of the Observational Method, the predictions are compared with the documented outcome after rock excavation to permit an assessment of whether conditions are acceptable. This process is carried out continuously as the construction work proceeds with the purpose of detailed adapation to the final repository to the structures and properties of the rock. The focus in the modelling work may vary depending on what questions and uncertainties need to be dealt with.

3.2.1 Overall strategies

Important premises for site descriptive modelling are presented in /SKB 2000, 2001a/. The result of the site investigation in the form of the site description for Forsmark /SKB 2008a/ serves as the point of departure for all further modelling during construction and operation. The description of confidence and remaining uncertainties /SKB 2008b/ provides a basis for identification of what new data need to be collected and where and with what frequency/resolution (depending on the facility part) this should be done. The strategies for analysis and modelling that have been employed and further developed during the site investigation phase have generally worked well and are expected for the most part to be applicable also during construction and operation. However, further development of strategies, methodology and tools will be required in view of the fact that new types of data and new work schemes will be introduced. These aspects are discussed briefly in Section 7.2.

The primary data needed (see also Section 2.1) range from the data required to set up the geological model – providing basic description of geometry, spatial distribution of rock types, fracture systems and deformation zones – to data on properties that characterise the ability of the rock to retard and retain released radionuclides, see Table 3-1. Other essential primary data describe the mechanical

Table 3-1. Examples of links between primary data and modelled objects.

Discipline	Type of primary data	Update and refinement of following models/descriptions
Geology	Properties of soil and bedrock (geometry, texture, mineralogy, geochemistry), character of ductile deformation, properties of fractures (geometry, mineralogy) and properties of different kinds of deformation zones (geometry, geology/mineralogy).	Soil depth and Quaternary stratigraphy. Rock domains, deterministic deformation zones and fracture domains with associated discrete fracture networks (DFNs)* between deterministic deformation zones.
Rock mechanics	Deformation properties and strength of the bedrock as well as orientation and magnitudes of the stress field.	Strength, deformation properties and other rock mechanics properties of intact rock, naturally fractured rock mass, individual fractures and deformation zones with link to defined rock domains/fracture domains. Rock stress model.
Thermal properties of the rock	Thermal properties (mineralogy/density, thermal conductivity and heat capacity) of rocks occurring at the site.	The thermal properties of the bedrock associated with defined rock type distributions in rock domains.
Hydrogeology	Hydraulic properties of soil and bedrock obtained from hydraulic tests. Estimation of flow porosity (if necessary). Groundwater pressure in soil and rock.	Subdivision into hydraulic units (soil layers, deformation zones and rock between deformation zones, including description with DFN) with associated property description.
Hydrogeochemistry	Concentration of solutes, including isotopes and dissolved gases, colloids and microbes.	Types of groundwater and pore water and their spatial distribution in soil and rock. Chemical processes and reactions (equilibrium modelling). Evaluation of ongoing and historical processes that contribute to today's groundwater composition.
Transport properties	Diffusivity (incl. determinations of in situ resistivity) and sorption properties as well as porosity (incl. zones with immobile water).	Retention properties of soil, matrix rock, fractures and deformation zones.
Properties of the surface system	Meteorological, hydrological and hydrochemical data (from continued monitoring) and possibly certain surface ecological data (e.g. soil and bottom sediment data from wetlands).	Description of surface systems and assignment of boundary conditions (mainly hydraulic) to models of the rock.

* DFN = *Discrete Fracture Network*, i.e. stochastic description of fracture networks and minor deformation zones.

strength of the rock, thermal conductivity, water-conducting capacity (expressed as hydraulic conductivity or transmissivity) and hydrogeochemical processes. Important state variables include temperature, groundwater pressure and rock stress. These are all important, both for the stability of the facility and for the long-term safety of the final repository.

The modelling that may be done during detailed characterisation is exemplified in general terms in the summary of model scales in this section (see below). Established models serve as a basis for construction, safety assessment and monitoring of environmental impact, where the degree of detail varies depending on the facility part in question. The main process *Safety Assessment* is only activated on special occasions, but relevant primary data and models for this application are continuously being added to the relevant databases.

On the tunnel scale (Figures 3-1 and 3-2), information collected from tunnels and other underground openings is continuously integrated. This may include information from deposition tunnels and associated deposition holes in high resolution. An intermediate deposition area scale (Figure 3-1) is used to describe individual repository parts (the central area and deposition areas), where the information from modelled objects on the tunnel scale is integrated. The deposition area scale is of central importance for detailed design/planning, prediction/follow-up and management of the construction process. Local and regional model volumes coincide with those used during the site investigation, with the difference that the repository's underground parts are now fully represented, and that the size of the model volumes will presumably be reduced. Both of these model scales are utilised for large-scale integration of geological, hydrogeological and hydrogeochemical information in particular, and for hydrogeological simulation. Examples of applied modelling during the successive construction of the repository are given in Chapter 4.

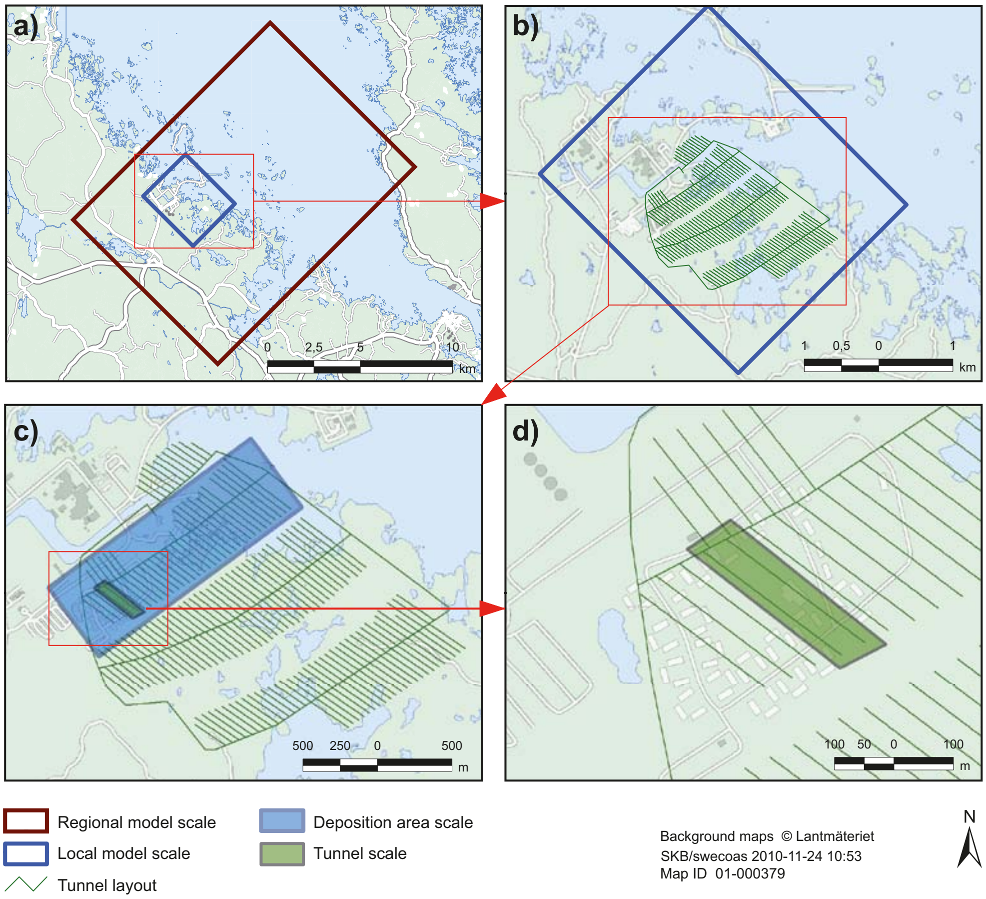


Figure 3-1. *Schematic illustration of different model scales. Inset (a) shows regional and local model scales. Inset (b) shows the local model area with the projected repository area. Inset (c) shows the reference layout at a higher resolution and also indicates the deposition area scale. Inset (d) shows an enlarged portion of the deposition area including a number of deposition tunnels (tunnel scale). See also summary of possible model scales on previous page.*

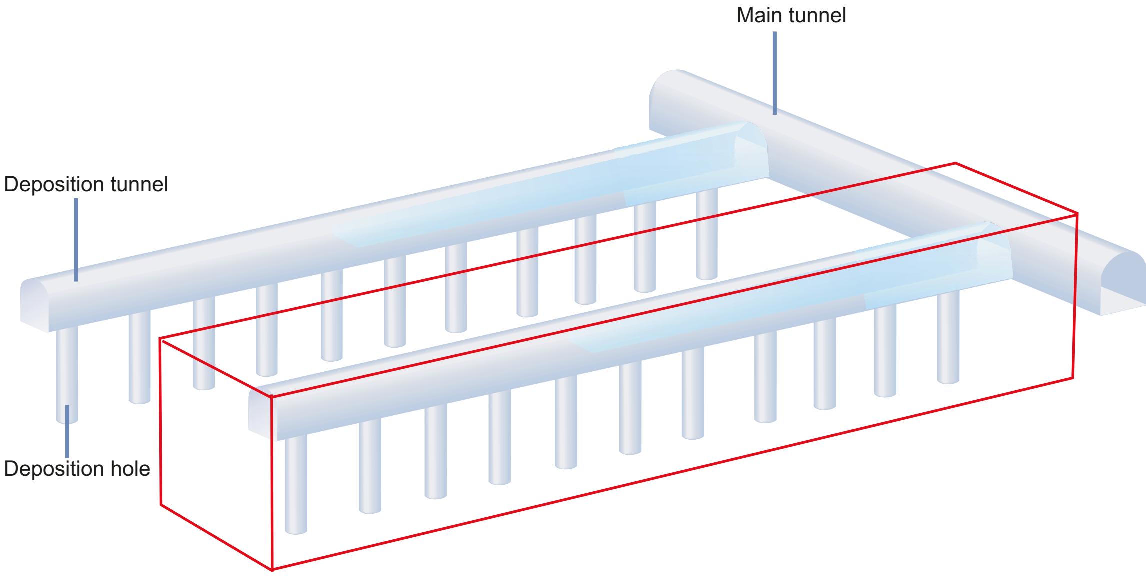


Figure 3-2. *Schematic 3D representation of tunnel scale (red). Models on the tunnel scale can, for example, include a single deposition tunnel or a varying number of deposition tunnels, depending on the nature of the problem.*

Summary of possible model scales.

Outline in principle of models, model concepts and model scales applicable to a final repository at Forsmark with exemplification of the possible areas of application of the different models during construction and operation (see also Table 3-1 and Figures 3-1 and 3-2).

1. **Site descriptive model** (also called **site descriptive model**): Collective term mainly for models on a regional or local scale (points 2 and 3), but in practice includes models on all model scales. The term applies to models which together provide the main basis for a site description, particularly in conjunction with the execution of safety assessments.
2. **Models on the regional scale (model volume ~ 300 km^3):** Cover the final repository (with underground facilities) and its regional environs. A similar model volume has been employed during the site investigation phase (~150 km^2). Models on this scale are based on the site investigation's regional models (mainly from geology, hydrogeology and conceptual hydrogeochemical description). These models are used and updated very rarely, and mainly in conjunction with updated safety assessments or other special needs.
3. **Models on the local scale (model volume ~ 10 km^3):** This model scale is based on the local models of the site descriptive modelling /SKB 2008a/, with the difference that the local model volume may be reduced and the final repository's underground facilities are described in full. The model is updated regularly, mainly with data from the models on the deposition area scale, as the final repository is expanded. This model scale serves as a basis for updated safety assessments, but may also be suitable for assessment of the environmental impact of the facility. Also serves as a general reference for models on smaller scales and is used for review and quality assurance of these models. The area of the model volume is about 10 km^2 and the depth about 1,100 m, see Figure 3-1.
4. **Models on the deposition area scale (model volume ~ 0.2 km^3)**: This scale covers an individual facility part, such as the central area, or an individual deposition area, see Figure 3-1, and thereby comprises a part of the local model but contains more information. The size of a "deposition area volume" is determined by the areal extent of the facility part in question as well as its vertical extent (roughly estimated at about 100 m). Models on the deposition area scale provide a basis for detailed planning and decisions regarding the execution (construction) of underground openings. It is mainly against models on this scale that the Observational Method's predictions are made. Models on this scale are continuously updated during construction with information from models on the *tunnel scale*, see point 5. After the position of a deposition hole in a given deposition tunnel has been determined, the updated model on the *deposition area scale* serves as a basis for management of construction and documentation. The collective compilation of information from models on the tunnel scale to the deposition area scale will eventually serve as a basis for the final documentation of the entire final repository.

   It is expected that the length resolution of deterministic deformation zones will be improved with the use of additional data. This will make it possible to model smaller zones (minor deformation zones incl. "large fractures") deterministically to a greater extent, above all in deposition areas.
5. **Models on the tunnel scale (model volume ~ 0.00002–0.0001 km^3):** *The tunnel scale* (see Figures 3-1 and 3-2) covers individual underground openings with nearby rock. The work may, for example, include predictions of tunnel/shaft intervals for site understanding, descriptive models of deposition tunnels, groups of deposition holes or the situation around individual deposition holes. These models are continuously updated with new information collected in conjunction with probe drilling and tunnel mapping, and are gradually built up as construction of the facility proceeds. Conceptual data for analysis of *"large fractures"* near the tunnel are collected and analyzed on this scale. Detailed models on the *tunnel scale* can also be utilised for safety-related assessments that influence decisions linked to the deposition process.

Information in the more detailed models is integrated in models that cover a larger portion of the facility, which means that the information, in particular geometric information, is virtually continuous over the boundaries of the models, but the topological representation and the level of detail (resolution) differs between the model scales. This applies in particular to the geological and hydrogeological models. Certain numerical simulation models, for example the regional flow model, may contain a DFN description (DFN = *Discrete Fracture Network,* i.e. brittle, stochastically described fracture networks and minor deformation zones) embedded in a continuum model, where boundary conditions are transferred internally to the DFN model.

For each model scale there are high requirements on resolution (not to be confused with accuracy and precision) that mainly relate to objects in the geological models (e.g. fracture length and length of deformation zones), but that can also be linked to objects in the other discipline-specific models (see Table 3-1). The choice of resolution for a given parameter on a given scale is in part dependent on technical considerations, e.g. the nature of the model problem, the size of the model volume, the number of manageable deterministic objects and resolution on an underlying smaller model scale. This can affect both which model scales will be used and chosen resolutions for them. In addition, there are also varying requirements on resolution depending on which geodiscipline and parameter and which facility part is being studied. In general, a higher resolution is applied to models that include deposition areas, including rock volumes around deposition holes.

What will mainly distinguish the different scales is the degree of determinism. On the detailed model scales, it is expected that the descriptions that are for the most part stochastic today, will gradually become more deterministic. This means, for example, that a primarily stochastic DFN on the tunnel scale will be replaced by a more deterministic model conditioned on fractures visible on the tunnel surfaces, but otherwise stochastic between the tunnels. The information from tunnel mapping also makes a valuable contribution to reducing uncertainties regarding the size of fractures.

For each model scale, a selection of discipline-specific models is in turn set up according to the needs of the user. The number of such models can vary for the different scales and the facility part in question, where the construction of a given discipline-specific model on a given model scale is governed by method descriptions for modelling. The deterministic geological models comprise the geometric foundation on which other disciplines build their models. The geological framework of the models consists primarily of geological domains based on deterministic deformation zones and the distribution of rock volumes between them. The discipline-specific descriptions are integrated to interdisciplinary descriptions on occasions that can be different for different model scales.

The local model is progressively updated with information from more high-resolution models, and used as a basis for design and detailed planning. The regional geological models are expected to be relatively static for the most part. The regional hydrogeological models, on the other hand, are updated as necessary based on the local-scale update and used for analysis of hydraulic and hydrogeochemical environmental impact. It should be pointed out in this context that the density of information outside the Forsmark lens is relatively limited, which can necessitate supplementary investigations and the need to update the local model.

It is essential that the collection of information and descriptive modelling on the tunnel scale comprise an integrated, interdisciplinary process. This way of working is conducive to the formulation of relevant hypotheses which are then followed up in modelling and further investigations and evaluation. In view of the fact that data collection and modelling will take place over a long period of time, it is important to ensure continuity as well as transfer of skills and experience, and thereby quality, during the entire period of construction and operation.

The flow of information from data collection via initial primary data verification to databases, and further to models and site descriptions at given decision points, will be managed within the framework of SKB's quality system. This will include the preparation of control plans (general and object-specific) for planned modelling steps, see Section 5.4.

3.2.2 Interdisciplinary integration

Site descriptive modelling based on investigations from the surface involves interdisciplinary interpretation of geological, rock mechanical, thermal, hydrogeological and hydrogeochemical properties, as well as of the transport properties of the rock and the surface system, utilising surface information and data from deep boreholes. Strategies and methodology for site descriptive modelling were developed for the site investigations at Forsmark and Laxemar, along with a strategy for integrated modelling /Andersson 2003/. Applications in site descriptive modelling at Forsmark and Laxemar are discussed in /Andersson et al. 2007/.

During detailed site characterisation, a large quantity of additional information will be collected in boreholes and underground openings. A higher resolution and a progressively increasing degree of determinism compared with the site investigations are expected during construction and operation, particularly in the deposition areas. Interpretations of common information from boreholes and tunnels, similar to the single-hole interpretation for cored boreholes that was carried out during the site investigations, are important in arriving at even more integrated descriptions based on geological, hydrogeological and rock mechanical data, of for example water-conducting structures and rock stress variations. As a natural extension of this approach, modelling and description of brittle deterministic deformation zones and discrete fracture networks (DFNs) will be carried out with a pronounced interdisciplinary orientation during the detailed site characterisation.

During the site investigation phase, seminars focused on reliability (confidence) and uncertainties associated with established models were held when a given version of the site descriptive model was terminated. The seminars and their documentation have constituted important factors in the integration work, as well as for refinement of the modelling methodology. It is foreseen that recurrent seminars of this kind will be held as a part of the modelling work also during the detailed site characterisation.

3.3 Investigation methods

Figure 3-3 presents a selection of programme and methodology reports written in preparation for previous investigation campaigns or as a summary of them, but where the contents are largely judged to be relevant also to the investigations that will be carried out during construction and operation of the final repository. In many cases, however, the methods need to be modified and upgraded, due to further technology development or new performance requirements. The green boxes in the figure

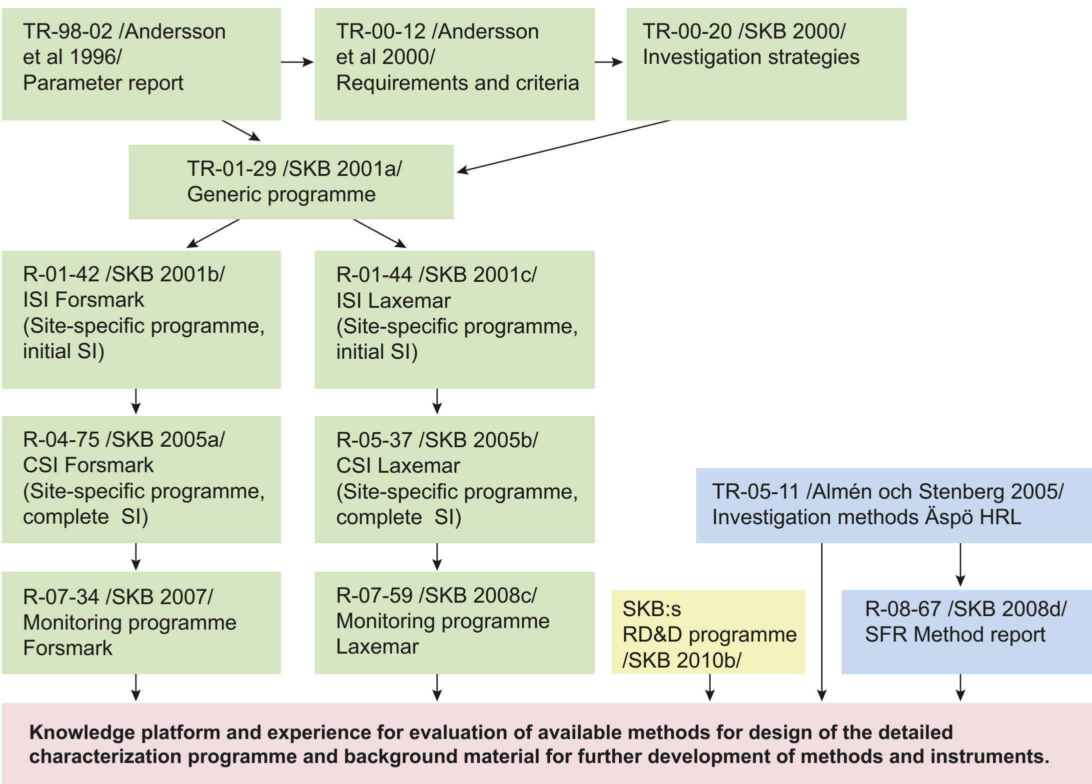


Figure 3-3. *Selection of SKB reports on investigation methods and instruments.*

represent reports related to the site investigations at Forsmark and Laxemar, which were completely focused on investigations from the ground surface. Even though detailed site characterisation during the construction and operation of the final repository will be dominated by underground investigations, these reports constitute an important basis for the detailed characterisation programme. The reports in the blue boxes describe methods and instruments intended mainly for underground conditions, while the yellow box represents the programmes for research, development and demonstration which SKB regularly submits to the Government. Even though the practical execution of different investigations under ground differs from their execution in surface investigations, it is often the same parameters that are to be determined in both cases, and the measurement principles are often identical.

Appendix 3 presents an overview of methods and instruments at SKB's disposal which SKB has primarily employed during the site investigations at Forsmark and Oskarshamn and in the Äspö HRL and SFR, and which are expected to be of use in the detailed characterisation programme as well, although in modified form in some cases. For more systematic and comprehensive accounts, see the reports in Figure 3-3, especially /SKB 2001a, Almén and Stenberg 2005/.

The method compilation in Appendix 3 describes in general terms:

- Drilling.
- Borehole investigations connected with drilling.
- Geological and geophysical borehole investigations.
- Rock mechanical investigations.
- Thermal investigations.
- Hydrogeological borehole investigations.
- Hydrogeochemical investigations.
- Investigations concerning transport properties of the bedrock.
- Mapping of underground openings.
- Non-borehole-related surface investigations.
- Monitoring.
- Geodetic investigations.

The most prioritized development needs are presented in Section 7.3.

Surface ecological investigations are also included in the detailed characterisation programme. Their situation is a special one, however, in that most of the data needed for safety assessment have already been gathered during the site investigations. The need for supplementary data and modified methods will not be established until at a later time. An exception is surface ecological monitoring, an activity that was initiated during the site investigation at Forsmark and is still in progress, see Table A3-1 in Appendix 3.

In general it can be said about the detailed characterisation programme that investigations conducted under ground will overshadow surface-based investigations. An exception to the rule is monitoring, which will be of considerable scope both below and above ground. A large number of boreholes from the site investigation will be used for monitoring of groundwater levels and of hydrogeochemical parameters.

3.4 Tools for data handling, data storage and modelling

Large quantities of investigation data of various kinds will be generated during construction and operation of the final repository. In addition to the fact that efficient database structures and data transfer systems must be developed and tested, it is essential that quality assurance procedures be adopted, see Sections 5.3 and 5.4. Furthermore, robust, efficient and user-friendly tools are needed for visualisation, modelling and presentation of geoscientific data and modelling results in 2D and 3D. Requirement specifications for the data systems will also take into account factors such as data security and modelling efficiency.

The data systems must incorporate solutions that permit easy retrieval and digital presentation of investigation results on which decisions are to be based. Due to the large quantities of data that will be produced, servers, networks and computers must also have the necessary capacity and redundancy.

SKB has started planning of the further development work that is needed in the area of computer tools for detailed characterisation with mapping of work processes for investigations and modelling, see Figure 3-4. The purpose is to identify data flows, information quantities and links between different types of investigations, modelling, design and construction, particularly with respect to the information flows associated with the use of the Observational Method. Based on this process survey and inventory of needs, decisions will be made on which development initiatives are to be undertaken. But a rough idea of what is needed already exists today, see Section 7.4. The development work begins with the formulation of requirement specifications, plans of action and plans for performance testing. In addition to testing of the different individual units in the data system, integrated testing will be carried out.

The Äspö HRL will play an important role in development and performance testing, along with planned cooperation with Posiva. Most systems have to be developed and tested before the start of construction. The process survey also has a bearing on the work with quality systems, which is further described in Chapter 5.

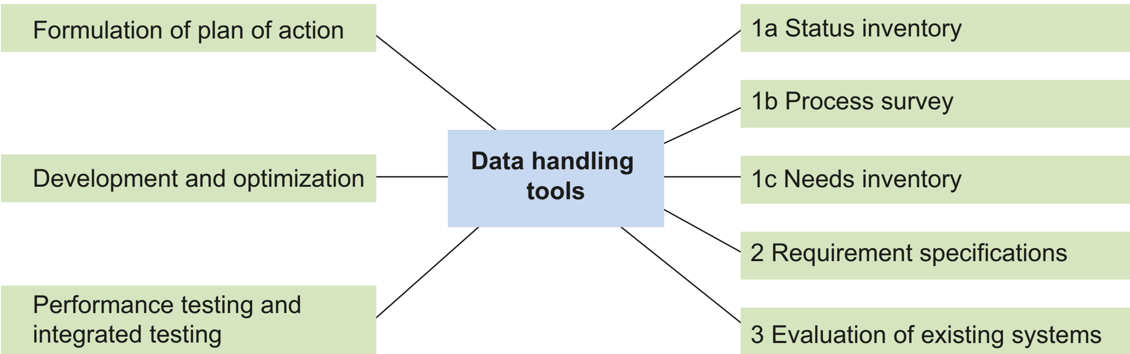


Figure 3-4. *Activities in development of data system.*

4 Detailed characterisation during different stages of construction and operation

4.1 Introduction

This chapter describes how detailed characterisation is proposed to be carried out during construction and operation of the final repository, in the light of current knowledge and technology. The detailed characterisation programme will be subject to revision and adjustment up until the start of the construction work for the final repository, and even after that there will be further development and changes. These changes will be described in subsequent versions of the programme.

Figure 4-1 illustrates the geological situation and the reference layout for a final repository at Forsmark. The points of departure for the programme are the reference design of the facility and the questions that have arisen against the background of the design premises for each facility part /SKB 2009b/, as well as the uncertainties presented in the site descriptive model /SKB 2008a, b/.

Section 4.2 provides a general description of investigations and modelling regardless of facility part. The emphasis is on the routine investigations that will be conducted in a similar manner in the entire repository. Monitoring is also presented in this section, since it is performed in the same way regardless of facility part, and furthermore continuously during construction, or at least during long periods of these phases. Finally, a brief description is provided of the general role of modelling.

The detailed characterisation proposed to be done in accesses, central area and repository area is described in the following Sections 4.3–4.5. Figure 1-4 shows the preliminary layout of these facility parts. The structure is essentially the same for each facility part:

- Questions, uncertainties and design premises.
- Detailed characterisation in conjunction with construction.

In some cases the regular investigations within the construction process need to be supplemented with additional information for safety assessments. This is dealt with briefly in Section 4.6.

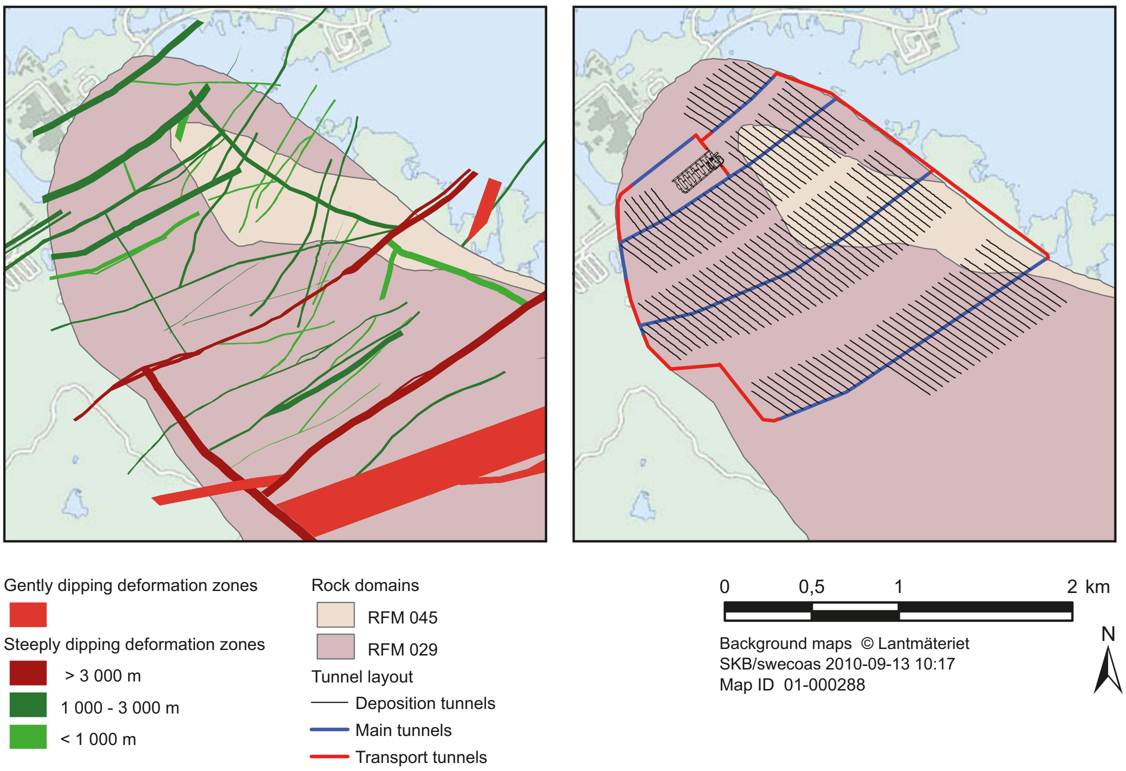


Figure 4-1. *Geological situation with rock domains and deformation zones at repository depth and reference layout for the facility.*

4.2 Detailed characterisation – general

By "detailed characterisation in conjunction with construction" is meant investigations and modelling needed to obtain sufficient information as a basis for design and construction as well as documentation of finished facility parts. The design processes uses information mainly from borehole investigations and existing models. As construction proceeds, this information is supplemented by tunnel mapping and other investigations at the tunnel face. This information is used for detailed adaptation of the facility to the properties of the rock in order to meet requirements on long-term safety. The detailed boundaries of the tectonic lens, the respect distance to major deformation zones, the existence of "large fractures" and of conductive fractures, the distribution of amphibolite and other rock types that differ from the principal rock types, and the rock stress situation are examples of important questions for site adaptation that must be addressed.

4.2.1 Routine investigations

Routine investigations comprise a part of the cyclical construction process. In principle they follow the same pattern all the time, but may need to be adapted and modified as experience and new knowledge is gained over the years. The following main elements are included, see Figure 4-2:

- Pilot hole drilling with investigations.
- Investigations in probe holes and grouting holes.
- Tunnel mapping.
- Installations and continued monitoring.

Pilot holes with associated investigations will be made in the deposition areas and in the shafts. In the ramp and central area, pilot holes will be drilled as needed, in response to whatever uncertainties exist along the remaining tunnel route. The pilot holes consist of cored boreholes 200–300 metres in length, except for the longer holes that are drilled in shaft positions.

Probe holes will be drilled to a preliminary length of 20–25 m, equivalent to the advance made in several (4–5) blasting cycles. The results from boreholes and investigations will provide data for planning of any pre-grouting. All boreholes will be drilled inside the planned tunnel contour. The rough sequence of routine pilot and probe hole drilling is illustrated in Figure A3-3 in Appendix 3.

Tunnel mapping is carried out as an integral part of the tunnelling cycle. In addition to geometric documentation and bedrock geological mapping, water seepage is documented and rock and water quality is assessed. Tunnel mapping is performed routinely and continuously in all underground openings. Coordination between investigations is particularly important in the ramp and the skip shaft (the shaft that will be used for hoisting of blast rubble), since only one tunnel/shaft face is available. Rock support measures are also documented in conjunction with tunnel mapping.

Along with the investigation results from boreholes, tunnel mapping is the most important source of information for the routine updating of detailed-scale models, see Section 3.2. The objective is that updating should be done so that detailed planning of continued construction can always be based on relevant comparisons between predictions and outcomes in accordance with the principles of the Observational Method. The logistics of tunnel mapping in deposition tunnels can to some extent be arranged differently than for other underground openings, see Section 4.5.5.

Installation of measurement equipment and initiation of measurement programmes for new measurement points is done above all in the areas of groundwater monitoring (groundwater pressure, inflow and salinity) and rock mechanics.

4.2.2 Modelling

The investigations generate primary data, i.e. measurement data and routinely calculated values for individual measurement objects (e.g. boreholes) or areas (e.g. tunnel walls). All primary data are stored in SKB's primary database. Primary data are the basis of all modelling. Modelling involves analysis of point and area information so that the properties of the bedrock and natural processes can be described. It is the models, together with underlying primary data, that provide the basis for design, follow-up and guidance during construction and for safety assessments. The methodology and execution of modelling is described in Section 3.2 and Appendix 2 for different disciplines, integrated over geoscientific disciplines and on different scales.

Generalized work flow	Comments on construction and possible methods for investigations
Pilot drilling - MWD measuerments ↓ Investigation in pilot hole - Basic programme - Options	Pilot drilling by core drilling. Pilot holes are planned to be drilled selectively in accesses and the central area in response to whatever uncertainties exist along the remaining tunnel route. Pilot drilling is currently planned to be done in deposition areas for all main tunnels and deposition tunnels. The length of the pilot holes will vary according to needs and possibilities. 200-300 m can be regarded as typical lengths. The basic programme for investigations will be determined in the pilot holes, but after that methods can be added or omitted as needed. The basic programme includes Measurements While Drilling (MWD), borehole imaging (BIPS = Borehole Image Processing System), core mapping (Boremap), hydraulic tests and water sampling (selective), as well as modelling.
Probe drilling, grout hole drilling - MWD measurements ↓ Investigation in probe holes - Basic programme -Options	Probe drilling is always done routinely about every 4th or 5th blasting cycle in order to predict detailed rock conditions as the tunnel advances. A number of drilling parameters and flushing water parameters (MWD) suitable for assessing rock quality are recorded during drilling as a basis for grouting. MWD parameters are also recorded during grout hole drilling, as well as when control holes are drilled to assess the results of grouting. A basic programme will also be devised for investigations in the probe holes, and as in the case of the pilot holes the investigation programme can be modified. The investigations are mainly focused on the geological and hydraulic properties of the rock, but precisely defined methods have not yet been determined.
Blast hole drilling ↓ Blasting, mucking and scaling ↓ Tunnel mapping ↓ Rock support ↓ Updated model - tunnel scale	Generally, a blasting cycle includes rock excavation tasks (blast hole drilling, blasting, scaling, rock support) and detailed characterization tasks (tunnel mapping and modelling). The design requirements (such as geometry) vary depending on the facility part being built, so slightly different methodologies are used for rock excavation. The deposition tunnels have to meet the toughest requirements. Here the tunnel is blasted in two steps: first the top heading, then the bench. When the bench is removed in the deposition tunnels, a smooth tunnel floor must be created with a limited excavation-damaged zone. This is achieved by means of controlled blasting. Tunnel mapping is planned to be done after blasting, mucking and scaling. In the deposition tunnels, mapping will be done either before or after removal of the bench, or in two steps, which is also determined by other factors relating to the construction of the deposition tunnels. Here, for example, regular tunnel mapping will be supplemented by more detailed mapping after a deposition tunnel has been completed. In the access ramp, where the whole tunnel cross-section will be blasted out simultaneously and rock excavation will only be done at one tunnel face, the logistics is essential. Tunnels of different sizes will be built in the central area, and rock excavation can be pursued at several faces simultaneously, which means that the execution of tunnel mapping must be adapted to this. Mapping mainly focuses on rock types, fractures and deformation zones with associated properties. It is important to identify properties that can indicate the presence of "large fractures" (see Figure 4-8). All investigation results will be immediately processed so that models on the tunnel scale can also be updated regularly and compared with predictions to guide the continued tunnelling work according to the Observational Method.
Installations for monitoring	Installations of various kinds will be made in the underground openings, for both permanent and temporary use. They include weirs with monitoring system, which are installed to measure the inflow of water. Preliminarily, they will be positioned every 500 metres on the ramp, while each deposition tunnel will have its own weir. Groundwater pressure measurements in boreholes are another example of what the underground monitoring system will include.

Figure 4-2. *Generalized work flow for rock excavation works and routine investigations during the construction phase.*

Generally, routine modelling entails that models are updated on a detailed scale based on probe drilling and tunnel mapping. By comparison of actual results with predictions, these models provide a basis for the continued construction work. When models on large scales are updated, information from pilot drilling or other investigation drilling is also used. Even more extensive modelling is done when, for example, safety assessments are to be updated, in which case site descriptive models on all scales are updated based on all relevant primary data.

In principle, all modelling work can be regarded as updating, where the previous model version is improved to a new model version with the aid of new and relevant primary data. Quality-assured data from monitoring comprise an essential part of the concept "new and relevant primary data".

4.2.3 Monitoring

General

By "monitoring" is meant long-term observation to record any changes. With regard to final disposal of spent nuclear fuel, SKB's definition of monitoring is:

"*Continuous or repeated observations or measurements of parameters to increase the scientific understanding of the site and the repository, to show compliance with requirements or for adaptation of plans in light of the monitoring results*" /Bäckblom and Almén 2004/.

During construction and operation, the final repository will affect the site's soil, bedrock and environment in different ways. Monitoring of changes contributes to continued, more detailed site characterisation, which in turn serves as a basis for detailed adaptation to the properties of the bedrock, for updated safety assessments and for determination of environmental impact. In order for the monitoring results to be used in this way, monitoring must have been done for a sufficiently long time before the start of construction of the repository in order to obtain a *baseline* for a number of parameters expected to be affected by the repository. Monitoring is planned to continue as long as the repository is in operation. The content and scope of the monitoring programme will vary in time and space as new deposition areas are built at the same time as deposition is under way in other parts, and deposition tunnels have already been backfilled and closed in yet other parts of the repository. When the whole repository has been closed, monitoring will be discontinued according to current plans, since a fundamental requirement on the final repository is that it should fulfil its safety function without surveillance.

Monitoring during construction and operation

At the start of construction, monitoring will already have been in progress for some time. The monitoring programme that will be implemented is largely a continuation of the programme that was carried out during the site investigation and is still in operation. In addition, monitoring will be extended to a number of new parameters and objects, mainly in the underground facility.

Monitoring includes a broad spectrum of investigations with the common denominator that the time-dependent variation of the observed parameter is of primary interest. One principal purpose is to identify whether and how the facility impacts the parameter in question. Other principal purposes are to provide detailed data for adaptation of the facility to the bedrock and to verify that the design premises are fulfilled.

Given the fact that the system for groundwater monitoring at Forsmark was built up during the period 2002–2007, the period of undisturbed monitoring data will cover many years before the start of construction of the final repository. As regards groundwater levels/pressures and the chemical composition of the groundwater, this means that natural (unaffected) variations will have been recorded for many years. This *baseline* comprises an extensive body of comparison material that makes it possible to identify changes related to the impact of the facility.

Table 4-1 provides a summary of the contents of the monitoring programme. Groundwater monitoring (mainly groundwater pressures, flows and chemistry) comprises a large part of the monitoring programme. Seismic monitoring is another type of monitoring. Monitoring is foreseen to be a continuous activity during construction of the final repository and as long as the repository is in operation. Just as important as adding monitoring parameters and objects as needed is removing monitoring objects when they are no longer warranted. The following sections provide a more detailed description of groundwater monitoring and seismic monitoring. Methods for monitoring are described in Appendix 3.

Table 4-1. Planned scope of the monitoring programme.

Monitoring	Measurement of	Comment
National seismic monitoring	Sudden natural rock movements such as earthquakes. Induced seismicity caused by blasting in the near-field will also be registered.	Performed within the framework of the Swedish National Seismic Network (SNSN). Has been going on for several decades and was supplemented in 2004 with a monitoring station within the Forsmark investigation area.
Local seismic monitoring	Sudden, natural and induced rock movements of lower magnitude than can be registered in the national network. Can be used to study small-scale earthquakes and to analyze the effects of blasting on local stress redistribution in the bedrock.	The monitoring system will be established before the start of construction.
Measurement of rock movements with GPS	Horizontal creep movements in the bedrock.	Performed with the aid of GPS stations. Measurement has been going on at Forsmark since 2005.
Meteorological monitoring	Weather parameters – precipitation – air temperature – barometric pressure – wind speed – wind direction – relative humidity – global radiation – snow depth – water content of snow – time of ice freeze-up/break-up	The weather parameters (in addition to the snow and ice parameters) were recorded at two weather stations at Forsmark during the period 2003–2007, i.e. during much of the site investigation, and continued after that at one weather station. Snow measurements have been performed on three sites, and ice measurements on two sites, in the investigation area since 2003.
Hydrological monitoring	Water levels in surface water (streams, lakes and the Baltic Sea). Water flows in streams. EC (electrical conductivity) and temperature in surface water.	Performed during a large portion of the site investigation.
Groundwater monitoring (levels, pressures and flows)	Groundwater table in soil wells and boreholes. Groundwater pressure in packed-off borehole sections. Groundwater flow in packed-off borehole sections.	The monitoring system was gradually expanded during the site investigation. Groundwater monitoring will change over time as, for example, boreholes from the underground facility are added and may be monitored during shorter or longer periods.
Groundwater inflows to the facility	Water inflow and the electrical conductivity of the groundwater in connection with e.g.: – point seepage – seepage in tunnels or tunnel sections – seepage into deposition holes – seepage into the entire facility	The monitoring system will be installed and gradually expanded as construction of the facility proceeds. Deposition tunnels and deposition holes will be monitored after completion until they are ready for deposition.
Hydrogeochemical monitoring	Chemical and surface ecological parameters in: – precipitation – surface water – groundwater from soil wells and boreholes – water seeping into the facility	Monitoring was initiated and gradually expanded during the site investigation. Hydrogeochemical monitoring will change over time as, for example, boreholes from the underground facility are added and may be monitored during shorter or longer periods. Water seeping into the facility can be sampled from point seepage and from the drainage system.

Monitoring of groundwater

Groundwater monitoring records pressure variations in the groundwater that reflect hydraulic connections in the bedrock. Monitoring data of this type serve as a basis for the further development of hydrological, hydrogeological and hydrogeochemical models, while also contributing to geological modelling (indicates geometry and properties of water-bearing deformation zones). The monitoring results are also used for calculations in the safety assessments. SKB's experience from the construction of SFR, Clab and the Äspö HRL has shown that changes in hydraulic conditions may have multiple, and sometimes interacting, causes. Some can be regarded as long-term trends (non-reversible), while others may be sudden (and sometimes unexpected) changes, which may be of either an irreversible or a reversible nature. The groundwater monitoring below ground is expected to resemble that which was done during the construction of the Äspö HRL /Almén and Stenberg 2005/. The scope of the monitoring programme will be regularly reviewed so that measurement objects can be added and removed as needed.

Groundwater monitoring was initiated early during the site investigation and was then gradually expanded to its present-day scope, which will remain more or less unchanged until the start of the construction phase of the final repository /SKB 2007/. Groundwater monitoring has resulted in a unique database that contains many years' recordings of variations in the groundwater table and deeper, unaffected natural variations in the pressure of the groundwater over time, as well as in its chemical composition. Furthermore, the monitoring programme has included parameters in surface water (levels and flows in brooks, lakes and the sea) as well as meteorological parameters. In addition, surface water and precipitation have been sampled for chemical analysis. This *baseline* provides the necessary basis for continued monitoring to demonstrate and follow the final repository's impact on the surrounding environment.

During the construction phase, the groundwater monitoring will be augmented with additional measurement objects, mainly under ground, temporarily during a longer or shorter time, or continuously. Due to the fact that most new boreholes will be drilled within future underground openings, there will be relatively few new boreholes where monitoring can be carried out over a long period of time. Within the deposition areas, the drilling programme will be coordinated with tunnel construction so that the pilot holes for the deposition tunnels can be monitored over such a long time that they furnish relevant information as a basis for decisions during the deposition process, see Section 4.5.5.

Monitoring of flow and chemical composition of seeping groundwater is planned in suitable sections along all tunnels, shafts and rock caverns in order to verify the design premises. Similarly, water inflow in deposition holes will also be measured, see further Section 4.5.6.

Seismic monitoring

Seismic monitoring was also performed during a large part of the site investigation phase. Seismic events at Forsmark's regional environs have been registered within the framework of the Swedish National Seismic Network, which was expanded during the period by a monitoring station at Forsmark /Bödvarsson 2009/. This activity will continue during construction and operation of the final repository.

Seismic monitoring may be supplemented by a local seismic network capable of registering seismic events of much lower magnitude. In addition to the accumulation of an earthquake database, measurement data from the local seismic network can contribute to a better understanding of the response of the near-field rock to tunnelling, which can provide greater knowledge of the properties of the local stress field. The local seismic network should be in place a year or so before the rock works commence.

4.3 Detailed characterisation – accesses

4.3.1 Questions, uncertainties and design premises

The near-surface rock within the Forsmark repository area, fracture domain FFM02 according to the site description, is characterised by a high frequency of gently dipping conductive fractures down to a maximum depth of about 150 m /SKB 2008a/. Below that, in the fracture domains FFM01 and FFM06, the rock is characterised by a very low frequency of conductive fractures.

High water inflows are expected in shafts and ramp in the contact between soil and rock in the near-surface rock, which could require extensive grouting /SKB 2009b/. The Design and Construction Report /SKB 2010a/ specifies maximum permissible water inflows to the facility's underground openings. Only in the case of the deposition tunnels is this requirement related to long-term safety. For other tunnels and shafts, the requirement states that the water volumes that must be pumped up from the facility must be reasonable from a technical and economic viewpoint. It is possible to reduce the water inflows by effective grouting, which limits drawdown in the superficial bedrock. This in turn reduces the risk of impacting the natural environment.

The accesses are located close to two minor deformation zones, but their properties are not expected to require any special investigations from a construction viewpoint.

4.3.2 Detailed characterisation in conjunction with construction

Detailed design

In view of the conditions described in Section 4.3.1, the following investigations are planned prior to or in conjunction with the detailed design of accesses.

- Supplementary investigation drilling (percussion drilling and/or core drilling) will be done from the ground surface in order to obtain additional data on the hydraulic properties in fracture domain FFM02. The borehole investigations will be performed in accordance with roughly the same measurement programme as during the site investigation. After completed borehole investigations, the boreholes will be instrumented for monitoring of groundwater level and pressure.
- Pilot holes for the skip shaft will be core-drilled down to repository depth. In the upper parts, the water-conducting properties in FFM02 are of the greatest interest. In the deeper parts it is important to confirm that no unexpected properties exist and to be able to make good predictions prior to shaft sinking. The pilot hole investigations will be performed in accordance with roughly the same measurement programme as during the site investigation. In the case of the access tunnel (the ramp) as well, an initial pilot hole will be drilled from the ground surface.

Furthermore, an assessment will be made as to whether the monitoring points in the soil layers are sufficient in number and correctly distributed to determine the impact of the facility on the groundwater levels. If necessary, supplementary monitoring wells will be installed.

Based on these and possibly other investigations, the geological, hydrogeological and rock mechanical models from the site investigation will be updated on applicable scales. Based on these models, the detailed design of the accesses can be completed and predictions made, e.g. regarding grouting measures in fracture domain FFM02.

Construction

When access tunnels and shafts are driven, the cyclical work process with routine investigations described in 4.2.1 and Figure 4-2 will be used. The presence of highly conductive fractures in fracture domain FFM02 underscores the importance of pilot drilling in this section. Based on results from these boreholes, pre-grouting can be planned so that the water inflows in tunnels and shafts do not exceed the maximum permissible values. Fulfilment of the requirement can be verified by subsequent monitoring of the water inflow at the weirs that are built at regular intervals. Possible effects at ground level in the form of lowered groundwater table will be checked by monitoring in soil wells and rock boreholes.

The fracture domains situated below FFM02 are not expected to yield large water flows. Pilot drilling is mainly planned when uncertainties regarding the location and properties of deformation zones are of importance for the construction process. Regarding investigations that may for other reasons be carried out in the accesses to the facility, see Section 4.3.3.

Since the shafts are driven using a different method than the tunnel ramp, the routine investigations will be adjusted for this. The skip shaft will be driven as a sunk shaft and is the facility part that will reach repository depth first, see Figure 4-3. Pilot and probe drilling with associated investigations will be done, and the shaft will be mapped with the same level of ambition as in the ramp. The experience gained from mapping of elevator and ventilation shafts at the Äspö HRL will be taken into account in detailed planning.

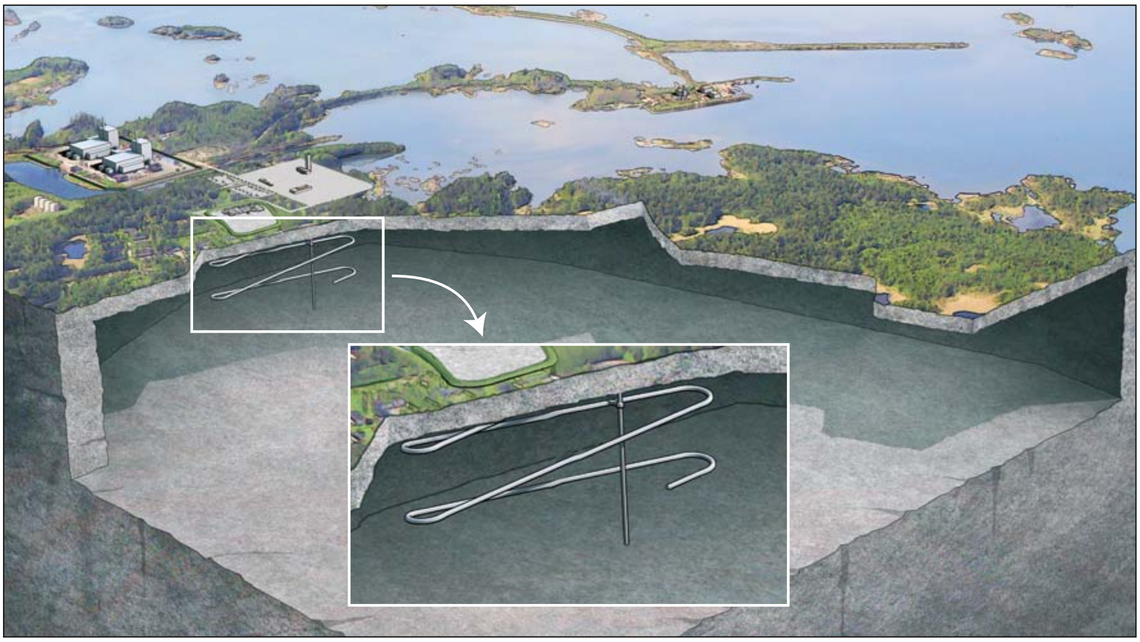


Figure 4-3. The accesses consist of ramp and shafts, of which the skip shaft is the part that first reaches repository depth.

The elevator and ventilation shafts will be driven by *raise drilling*. An alternative investigation programme will be devised for these shafts to meet a different information need, since both ramp and skip shaft will already have been built by then.

Models will be updated regularly during design and construction, see Section 4.2.2.

4.3.3 Other investigations in facility accesses

In addition to detailed characterisation to obtain information for design and construction of the accesses as described in 4.3.2, investigations relating to other facility parts may also be necessary, mainly for the deposition areas. It is also important to take the opportunity to test different investigation methods and instruments before they are to be used in the deposition process. This section presents some investigations that may be done in the facility's accesses or the central area's underground openings.

- Even though the excavation work is not yet near the deposition areas and they cannot be reached by boreholes, it is important while still on the way down to repository depth to measure the magnitudes and orientations of the rock stresses and how they change with depth /SKB 2009b/. This is elaborated on in Section 4.5.2. In addition to borehole investigations, other investigation methods intended especially for underground conditions may be employed. For example, convergence measurements will be performed in the skip shaft, since it is the facility part that first reaches repository depth. Measurement equipment for this will be installed at a number of levels and will probably be supplemented by overcoring so that these methods can be calibrated against each other.
- The site investigation's DFN models served as an important basis for calculating the frequency of *Minor Deformation Zones* (MDZs) and thereby also for estimating the frequency of "large fractures". The DFN models contain uncertainties, however, and regarding the design premise concerning "large fractures" it is possible that the criterion will be reformulated, see Appendix 1. Nearer repository depth, stress conditions and hydraulic properties are expected to be similar to those prevailing in the repository area. Fracture and flow data from pilot drilling and tunnel mapping in the lower part of the facility's accesses or in the central area can therefore serve as a basis for calibration of DFN models, reducing their uncertainties. More detailed fracture mapping is needed for this than that included in regular tunnel mapping.
- The methodology for identification of "large fractures" that cannot be accepted at a canister position is another example of methods that may need to be tested in the repository's accesses and in the central area, see more detailed description in Section 4.5.

It is important that methods and procedures for the recurrent investigations be tested and fine-adjusted during this early phase of repository construction. It is also urgent to establish good coordination with the rock works so that the work and information flows will be adequate and efficient.

In the case of the ramp, which only has one working face, each investigation aside from routine probe drilling and tunnel mapping necessitates an interruption in the excavation work, which means that the advantages of each such investigation must be weighed against the disadvantages. Investigations that provide information for safety evaluations and safety assessments have priority. Pilot drilling and other investigation drilling also necessitates interrupting the excavation work, unless a special niche or a short side tunnel can be built so that the investigation can be performed without causing interference. Working environment aspects will be particularly important in the case of the skip shaft, and this may influence which investigations can be performed.

A special niche or side tunnel is needed to permit early testing of the characterisation methods that will be used later in the deposition process. The central area offers greater opportunities for such tests and experiments, but the test results may be needed earlier. Posiva currently plans such a testing programme in ONKALO, and cooperation has been initiated regarding the benefit of different investigation methods. Non-site-dependent research and development with a bearing on the final repository will also be conducted at the Äspö HRL.

4.4 Detailed characterisation – central area

4.4.1 Questions, uncertainties and design premises

Since the central area is not subject to any special requirements regarding design premises for fulfilment of long-term safety, the main requirements on the rock concern the mechanical stability of the facility and water inflows during the final repository's operating period. The central area is located in rock domain RFM045 and fracture domain FFM06. Both have properties that are for the most part favourable with regard to mechanical stability. There is, however, some uncertainty regarding rock stress magnitudes at repository depth, so priority should be given to stability issues, particularly in the case of tunnels whose longitudinal axis intersects the direction of the greatest horizontal stress at a large angle.

The central area is expected to have some contact with the minor deformation zones ENE1061 and NNW1205. New knowledge regarding these zones will be obtained when they are intersected by the final repository's accesses. The frequency of conductive fractures is low in the fracture domains in question. Furthermore, the hydraulic properties of the aforementioned deformation zones will have been documented sufficiently once the accesses have been built, which means that it should be possible to handle the central area without any great difficulty.

4.4.2 Detailed characterisation in conjunction with construction

New data on rock conditions will be available for the detailed design of the central area. Of greatest importance, compared with the information that was available during design step D2, are the investigation results generated by the routine investigations during construction of the accesses. Feedback from investigation and construction serves as a basis for the detailed characterisation for the central area, see Figure 4-4. Whether or not any special investigation is needed prior to detailed design is dependent on what uncertainties may be identified. Regardless of whether new investigation results are obtained aside from routine ones, models will be updated and predictions made before the start of construction of the central area.

Routine investigations will be conducted during the construction of the tunnels and rock caverns of the central area, see Section 4.2.1. The focus will be on the parameters judged in design to be essential to guide the continued construction process, in accordance with the Observational Method. The principle is the same as when the accesses were built, but the methodology and the work flows will be adapted to the conditions prevailing in the different underground openings of the central area.

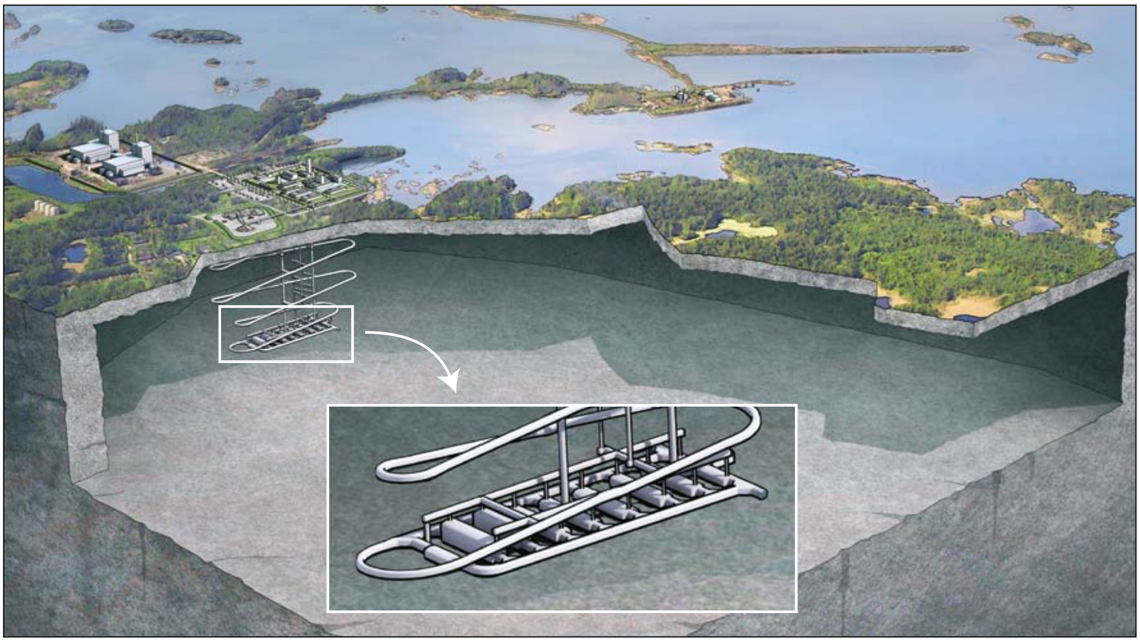


Figure 4-4. The final repository's central area contains a number of parallel rock caverns that can be used to test investigation methods for the deposition process.

4.4.3 Other investigations in the central area

For the same reasons as in the facility's accesses, investigations may be conducted to obtain information on the rock in the deposition areas. It was mentioned in Section 4.3.3 that the central area with its parallel rock caverns may be particularly suitable for testing of investigation and modelling methodology aimed at identifying and characterising "large fractures". For the first time, modelling can be done based on the investigation and construction of several parallel underground openings, a situation similar to the one that will prevail when deposition tunnels are built. An additional aspect for the central area is that this is the first opportunity to study the large-scale variation of thermal properties, mainly by means of geological mapping and if necessary also by means of laboratory analyses and rock samples, see also Section 4.5.2.

4.5 Detailed characterisation – repository area

4.5.1 Overview

This section deals with the role of detailed characterisation in the construction of the repository area, which is divided into a number of deposition areas. Figure 4-5 illustrates the gradual buildout of the repository area at a relatively early stage, when construction and deposition are under way in one deposition area at the same time as detailed characterisation is being carried out as a basis for the design of future facility parts.

The construction of each individual deposition area takes place in several steps, each of which consists of a number of deposition tunnels. This is shown in Figure 4-6, which also illustrates the fact that while deposition tunnels are being driven in one construction step, canisters are being deposited in the deposition tunnels that were excavated in the preceding step. The need for physical separation between construction activities and deposition activities is met by installing partition walls in the main tunnel, preventing contact between the two work areas. In order for materials to be transported to a work area, transport and main tunnels must first be built in the deposition area in question. Figure 4-7 shows the sequence in which the repository area will be built out /SKB 2009b/. From this it is clear how transport and main tunnel loops can be built within the deposition areas before deposition tunnels are built.

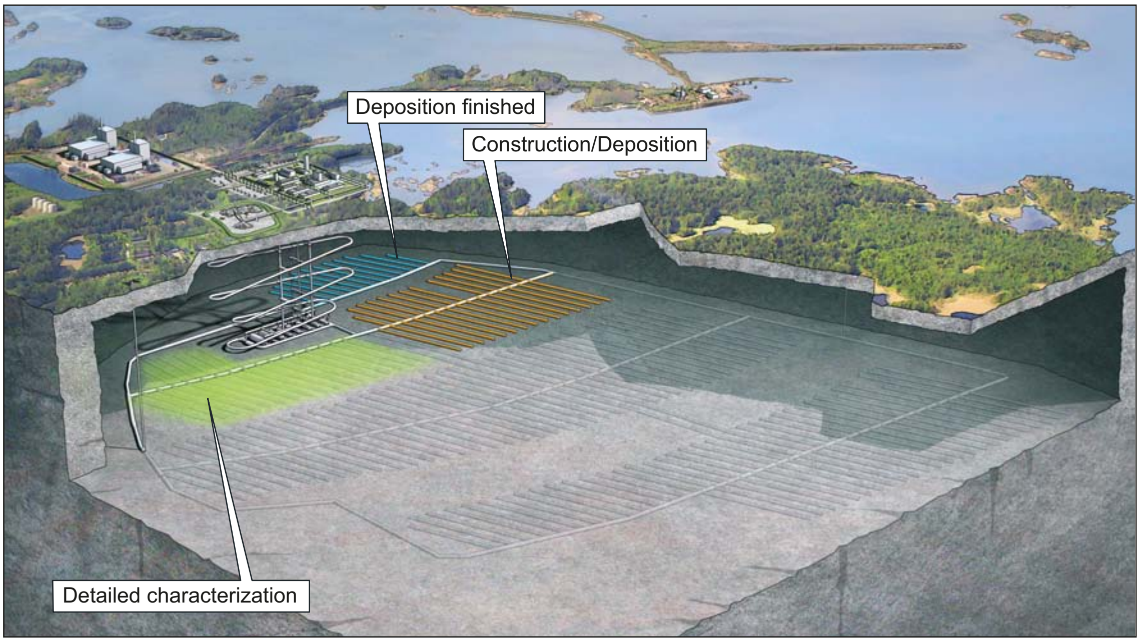


Figure 4-5. Illustration of simultaneous activities during the operating phase. Deposition has been finished in the blue deposition area. In the brown area, deposition is in progress in completed deposition tunnels at the same time as new deposition tunnels are being built and prepared for deposition. Investigations of various kinds are being conducted in the green area, for example in pilot holes, along with modelling for detailed planning of the next construction step.

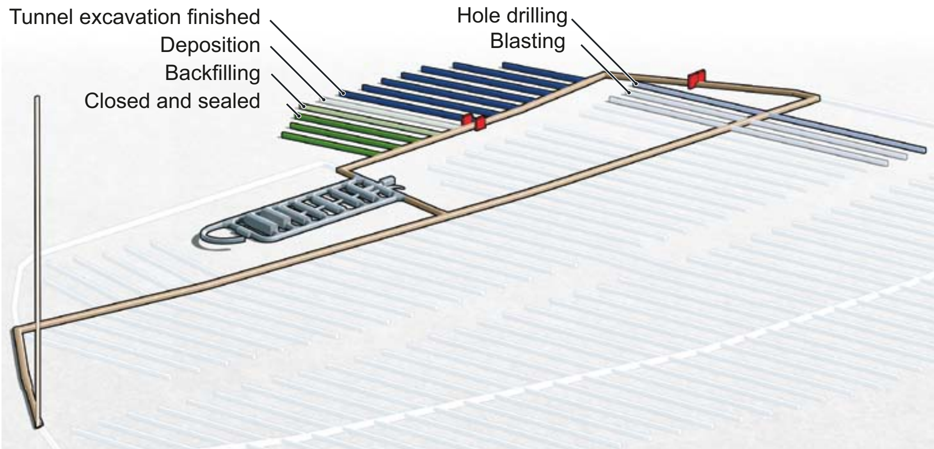


Figure 4-6. Illustration of the final repository during trial operation. The figure shows that underground construction is under way within one work area and deposition in another, and that these activities are separated from each other by partition walls. Prior to application for a licence for trial operation, the first tunnels nearest the central area are used for integrated testing.

The issues presented in Section 4.5.2 apply to all deposition areas. Only a small portion of the first deposition area will be built during the construction phase, and integrated testing will be performed in the first deposition tunnels, see Figure 4-6. This means that all investigation and modelling tasks will be tested together with setting-out, drilling and verification of deposition holes.

During this period a "data freeze" is also done for all information that will be used to update the site descriptive models and to update the Safety Assessment Report in preparation for the application for a licence for trial operation of the final repository. By "data freeze" is meant that all primary data available at a given point in time serve as a basis for the models and analyses that will be done within the framework of the safety assessment, similar to the methodology that was employed during the site investigation phase.

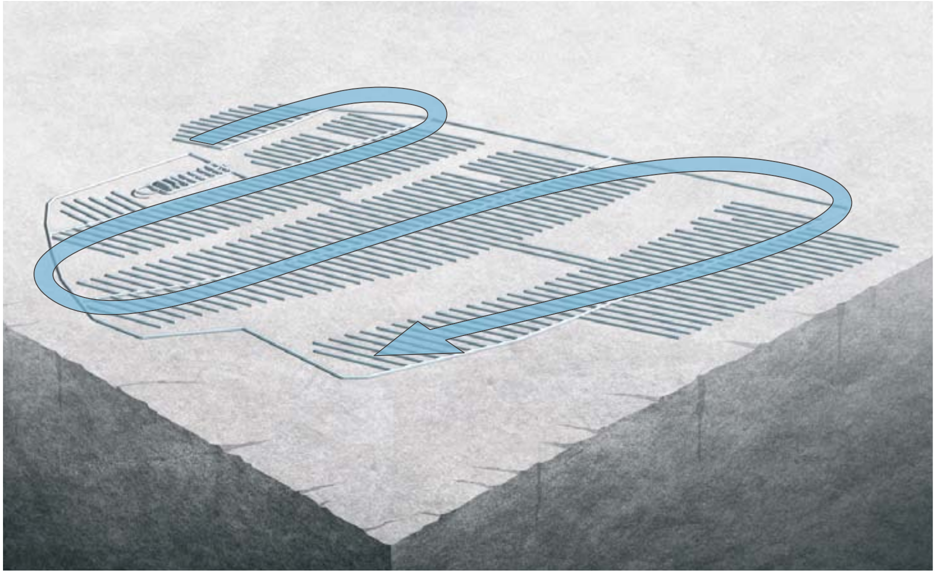


Figure 4-7. The figure shows the sequence in which the repository area is built out.

4.5.2 Issues related to design premises and uncertainties

Most of the design premises that apply to the bedrock concern the final repository's deposition areas, which will be adapted to the properties of the rock so that the overall requirements on long-term safety are met. Due to uncertainties in the relevant site descriptive model or to the fact that a higher degree of determinism is striven for, the site descriptive model will be updated, detailed and verified in several steps.

A summary presentation of essential issues that will, owing to their importance for the safety of the final repository and in view of the current uncertainties of the site descriptive model, be addressed during construction of the deposition areas. If the issue is also of relevance for other facility parts, it is in this section that it is treated more in its entirety. The discussion is grouped according to disciplines in the following order:

- Geology.
- Rock mechanics.
- Thermal properties.
- Hydrogeology.
- Hydrogeochemistry.
- Transport properties of the rock.
- EDZ.
- Geometric documentation.

Geology

According to the reference design, the final repository will be built within the rock domains RFM029 and RFM045, which belong to the tectonic lens at Forsmark. The first rock domain dominates in terms of volume, but both have favourable properties, see Figure 4-1. Together, and taking into account the loss of unsuitable canister positions, they must be able to accommodate the planned number of canisters /SKB 2009b/. The outer boundary of the tectonic lens is not sharply defined in relation to the surrounding bedrock. In order to enable the good properties of the rock domains to be exploited, these boundaries need to be determined in increasing detail as the deposition areas are built out.

The most essential properties of the prevailing rock types from a repository viewpoint are thermal conductivity and strength, both of which are deemed to be well known for each rock type. The distribution of the rock types in the rock volume will be determined in detail in the continued investigations, see further the section "Thermal properties".

According to the site descriptive model, the final repository bedrock at Forsmark is intersected by four deformation zones greater than three kilometres in length. The respect distance from these zones, within which canisters may not be deposited, is 100 metres. During construction of the deposition areas, the properties and locations of these deformation zones must be verified so that the requirement on respect distance can be met. The risk that there may be other, unidentified deformation zones of this size is assessed to be very low.

There are also a number of deformation zones with modelled lengths of between one and three kilometres. It is deemed unlikely that more such zones exist in addition to those already known. Canisters must not be emplaced in these deformation zones, but there are at present no requirements on respect distance nor any obstacles to driving deposition tunnels through these zones, provided sufficient rock support and sealing are carried out. Precise determination of the properties and locations of deformation zones is an important task for detailed characterisation.

Besides the 1–3 km long deformation zones mentioned above, there is another category of structural features that may not intersect a canister position: minor deformation zones (MDZs) and long uninterrupted fractures. Together they are designated "large fractures", and the problems surrounding them are described briefly in Section 2.1.1 and Appendix 1. It is assumed in the context of detailed characterisation that detailed fracture mapping for updating of DFN models is done. Most essential, however, is that each individual "large fracture" can be identified. Investigations are therefore planned to be done in several steps, so that it can be verified for each canister position that it is not intersected by a "large fracture", see Figure 4-8. Otherwise the canister position must be abandoned.

Rock mechanics

Some uncertainties remain concerning stress magnitudes at repository depth at Forsmark. However, the uncertainties regarding the orientation of the main stresses are assessed to be smaller. Stress analyses during design step D2 /SKB 2009b/ have shown that if the deposition tunnels are oriented within ±30 degrees of the orientation of the maximum horizontal stress, the risk of spalling in deposition holes is minimal for the most probable rock stress magnitudes. This has been an important principle in arriving at the repository's current reference design.

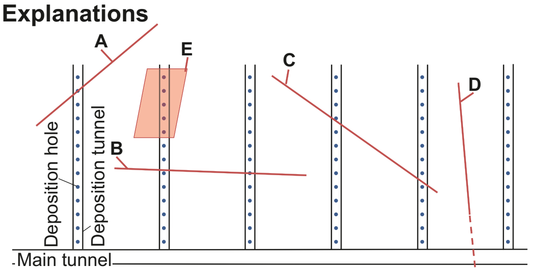
Supplementary characterisation of the stress field thus needs to be done, mainly to achieve greater certainty in the determinations of the magnitudes of the horizontal stresses, but also for more precise determination of the orientations. Both tasks are complex and require a combination of different measurement methods and observation of possible overloading in tunnels. It was noted in Section 4.3.3 that such investigations may be necessary already during the construction of the deeper parts of the final repository's accesses.

Thermal properties

The thermal conductivity of the rock is a design parameter that determines the distance (spacing) between deposition tunnels and between deposition holes. In the current reference design, this rock property entails that the spacing between the deposition holes is slightly greater in rock domain RFM45 than in RFM029.

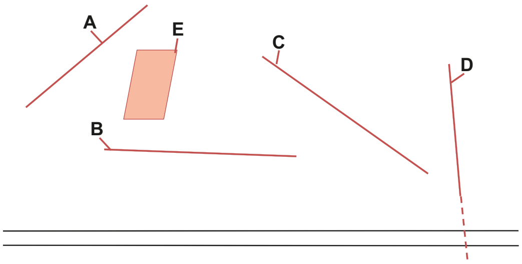
Amphibolite is a subordinate rock type in the repository volume with considerably poorer thermal conductivity than the granitic principal rock types. Amphibolite usually occurs as small lenses and is easy to recognise in mapping. If the amphibolite lenses were to occur more frequently than indicated by the site description, a larger total area would be needed for the deposition areas, but the risk of this is assessed to be small. Uncertainties regarding thermal conductivity are an essential question for detailed characterisation within the deposition areas. In general, however, the gradual expansion of the underground facility permits a virtually deterministic mapping of thermal conductivity and its spatial variation. Documentation of the occurrence of amphibolite dykes is thereby the most important task.

Explanations



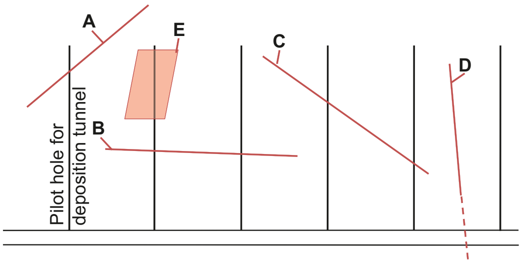
The diagram shows Examples of "large fractures" and how they intersect deposition tunnels and planned canister positions. Their "length" is on the order of 100 m. A-D may have different dips, and can then disqualify 1-3 canister positions. E is subhorizontal and intersects 5 or more canister positions. Orientation is important for their detection by measurement methods based on reflection, such as radar and seismic reflection.

Construction of main tunnel



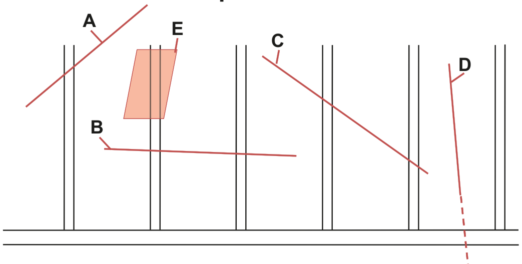
The diagram shows the step when a main tunnel is driven. The main tunnel is preceded by a pilot hole, in which drill core and hydrotest can indicate D. Radar and seismic reflection can detect B and C, which have a favourable orientation, but this also depends on their dip and geological properties. In probe holes, water-conducting sections can be indicated (D). Tunnel mapping shows FPIs and their properties and any water inflows are characterized (D). Radar and seismic measurements are performed from the tunnel (premises as above). Modelling on the tunnel scale is the ultimate tool for processing all data and assessing the lengths of the fractures.

Drilling of pilot holes for deposition tunnels



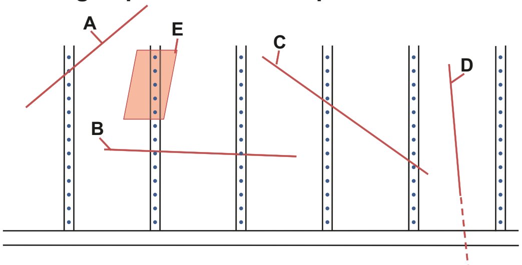
The diagram shows investigations during and after drilling of pilot holes for deposition tunnels. All "large fractures" that are drilled through can be detected from drill cores and other investigations as fractures or fracture zones (possibly transmissive), but their length cannot be determined (A, B, C). If they intersect two pilot holes and are transmissive, interference tests can indicate minimum length (B, C). Radar and seismic reflection can be used in different configurations. It should be possible to determine the orientation of A, C, D and E by reflection measurement. Modelling on the tunnel scale is the ultimate tool for processing all data and assessing lengths.

Construction of deposition tunnels



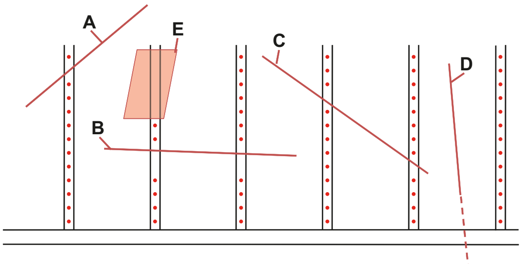
The diagram shows investigations in connection with the construction of deposition tunnels. Probe drilling gives the water flow rate (supplement to pilot hole). Tunnel mapping shows A, B and C as FPIs. Properties of these fracture surfaces are characterized and inflows are measured. Radar and seismic reflection can again be used in different configurations. It should be possible to determine the orientation of A, C, D and E by reflection measurement. E is now particularly important. Tomography could reveal additional properties. Modelling on the tunnel scale is the ultimate tool for processing all data and assessing lengths.

Drilling of pilot holes for deposition holes



The figure shows investigations during and after pilot drilling for deposition holes. Pilot drilling is avoided at positions where "large fractures" have previously been detected. Mapping and investigations show fractures and properties. E is penetrated by a hole for the first time. Special observations are made of possible "large fractures" from preceding steps. New radar and seismic measurements in different configurations. Interference tests during and after drilling reveal connectivity. Modelling on the tunnel scale is used to process all data and assess lengths.

Drilling of deposition holes



The figure shows that if the exemplified objects have been identified in the preceding steps and proved to be "large fractures" by means of integrated modelling, drilling of deposition holes can be avoided at these positions. If this has not been done, investigations can be performed in the deposition holes to clarify whether they can be approved or whether some holes have to be rejected. Hole mapping and inflow measurement, along with modelling, are the methods that are finally used. Radar and seismic reflection could possibly be used in a further step.

Figure 4-8. *Example of how the issue of "large fractures" with application of the EFPC criterion can be handled strategically by different types of investigations and modelling. (FPI and EFPC are explained in Section 2.1.1.)*

Hydrogeology

The water flow rate in the rock mass is generally low at repository depth within the fracture domains FFM01 and FFM06 and is therefore not expected to cause any problems for the construction and operation of the facility. The few water-bearing deformation zones that are expected should be able to be handled by grouting.

There are design premises regarding maximum permissible water inflows to deposition holes, shafts and tunnels, see Appendix 1. The limit on inflow to deposition holes is set with a view to the stability of the buffer before backfilling of the deposition tunnel. Furthermore, it is favourable for long-term safety if the deposition holes are positioned such that the future groundwater flow past them is small. It is therefore of great importance to know the location and permeability of possible future water pathways in the rock nearest the deposition holes. No quantitative requirements, other than those concerning inflow to deposition holes, have as yet been established, but this may change when the design premises are updated. The limit on inflow to tunnels and shafts applies per unit length and is set so that the backfill function as desired. There are also requirements on individual point inflows in deposition tunnels. But the inflow only needs to be limited when backfilling is being done, which can be achieved by grouting.

The limit on inflow to the central area's underground openings, shafts and other tunnels besides the deposition tunnels is determined by requirements on the working environment and on limited lowering of the groundwater table (drawdown). The limit on inflow to shafts and tunnels is also affected by the design of the closure. Based on requirements on the working environment and drawdown, this flow has been preliminarily set to ≤10 l/min and 100 metres of tunnel, see further the Design and Construction Report /SKB 2010a/.

Hydrogeochemistry

The chemical composition of the groundwater is of great importance for the function of the engineered barriers. Along with the geochemical properties of the fracture-filling minerals, this factor also influences the transport of radionuclides from the final repository to the recipient in the biosphere.

One design premise for the final repository concerns the groundwater composition in the bedrock where deposition positions are located, see Appendix 1. The requirement pertains to natural conditions prior to rock excavation. In general, when the facility is built, groundwater lowering will alter the natural hydrogeological conditions, which in turn causes a change in the spatial distribution of groundwaters of different compositions and leads to remixing. Some of the properties, for example redox conditions, are highly sensitive to disturbance, which means that measurement of the groundwater composition in individual deposition holes is of only limited value for verifying that the design premises are met. The most important verification of this is instead based on the results of the hydrogeochemical programme with associated modelling that was carried out during the site investigation, before construction of the underground facility started. Certain uncertainties remain regarding buffer capacity for redox and alkalinity along flow paths and the cause of elevated sulphide and uranium concentrations in a number of borehole sections. The planned sampling programme, like the site investigations, also includes investigations of microbes, colloids and dissolved gases. The sampling in the detailed characterisation programme, including hydrogeochemical monitoring, will quantify the changes in hydrogeochemical composition that are expected to occur.

Transport properties of the rock

No design premises related directly to the transport properties of the rock are defined for the final repository. In addition to the properties of the matrix rock and the fracture-filling minerals, the transport properties are largely determined by hydrogeochemical and hydrogeological conditions in the bedrock. Nuclide transport through the rock up to the biosphere was mentioned in the preceding section as an essential factor for long-term radiological safety. Supplementary information may be needed for future safety assessments, but probably only of a limited scope.

EDZ

By EDZ (*Excavation Damaged Zone*) is meant the damaged zone in the rock wall around tunnels and shafts that can be caused by blasting or an equivalent damaged zone that can be caused by mechanical rock excavation, such as drilling of deposition holes. Unfavourable rock stress conditions can also contribute to the formation of an EDZ in tunnels and deposition holes by spalling.

Certain design premises include hydraulic requirements on hydraulically connected EDZs in tunnels and deposition holes, see Appendix 1. One of them concerns maximum permissible permeability in the EDZ surrounding rock caverns. The requirement applies below the top seal, i.e. below the level up to which closure of the ramp and shafts will be done with sealing material. The requirement varies for different tunnels, shafts and other openings, where the most stringent requirement is made on the deposition tunnels, see further Appendix 1. A similar design premise regarding maximum permissible permeability exists for the excavation-damaged zone that may be formed around the deposition holes during drilling.

The chances of fulfilling the design premises for the EDZ are mainly dependent on the technology that will be used for rock excavation. Different investigations performed by SKB /SKB 2010a, Karlzén and Johansson 2010/ show that even though individual fractures may be formed in connection with rock excavation, they will not, assuming use of the planned reference method (blasting of tunnels and drilling of deposition holes), form a hydraulically connected zone over any great distance. It is assumed that some form of follow-up measurement of the properties of the EDZ will be done, but the methodology for this has not yet been determined.

Geometric documentation

There are a number of geometric requirements on the final repository's underground openings. In order for the buffer in the deposition holes and the backfill in the deposition tunnels to be emplaced correctly and fulfil the design premises, the dimensions of the openings must be kept within set tolerances, see Appendix 1. This imposes requirements on rock excavation and accuracy in coordinate measurement (equipment and methods).

Another geometric question is the position of the existing investigation boreholes, which have been drilled from the ground surface. In the case of those holes that will be located near a tunnel, accurate positioning is important.

4.5.3 Decision sequence and detailed development plans in connection with buildout of the repository area

Before and during the buildout of the repository area, the activity will be governed by a number of decisions in a sequence that starts with the construction of a deposition area and finishes with the approval of an individual deposition hole for canister deposition. The main decisions in this sequence are:

- Decision on boundaries of the deposition area prior to a buildout stage.
- Decision on location and construction of deposition tunnels.
- Decision on deposition positions in deposition tunnels.
- Decision on execution of deposition hole.
- Decision on approval of deposition hole for deposition of canister.

Information from detailed characterisation will constitute an important basis for these decisions. Figure 4-9 shows schematic relationships and information flows between – and important decision points for – detailed characterisation, design and construction activities. Both the relationships illustrated in the figure and the descriptions of the contents of detailed characterisation in the following sections are based on current knowledge and planning and should therefore be regarded as preliminary.

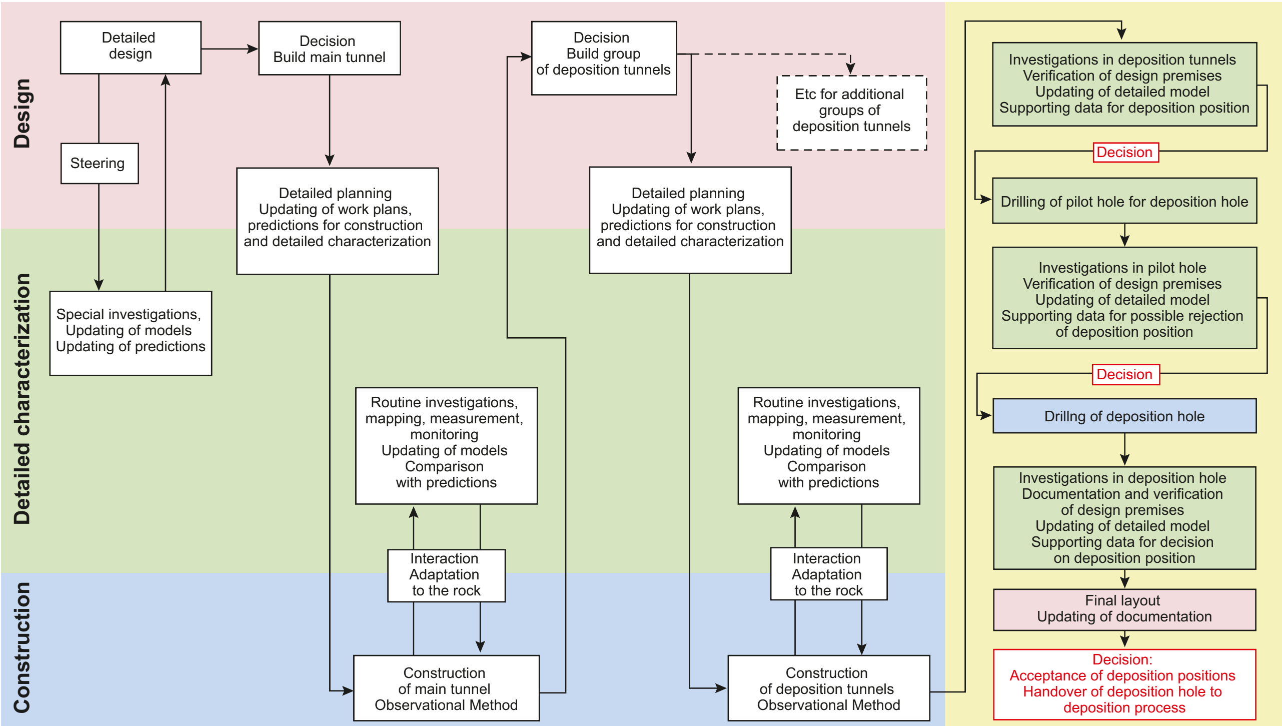


Figure 4-9. *Illustration of a schematic work flow for construction of a deposition area. The figure shows relationships between design, planning, detailed characterisation and construction as well as excavation and approval of deposition holes.*

Detailed planning of buildout step – general

When a decision is made to carry out a construction step, regardless of whether it involves a new deposition area or a group of deposition tunnels, detailed planning of the work is carried out. Detailed planning is based on existing design, updated models and documentation from facility parts built thus far.

In conjunction with the detailed planning, the requisite investigations and modelling work are ordered. Knowledge of the repository area will generally increase with time, but for certain properties the uncertainties differ in magnitude for different parts of the rock volume. Prior to each decision, relevant models should be updated with results from all investigations done thus far, both specifically ordered ones and ones performed routinely in conjunction with the construction work. Investigation boreholes can also be drilled from the ground surface, if this is preferable.

Detailed planning of a buildout step results in an updated work plan for construction and detailed characterisation with predictions and action plans in accordance with the principles of the Observational Method, see Section 1.4.4.

4.5.4 Detailed characterisation in conjunction with construction of transport and main tunnels for new deposition area

When a decision has been made to build a new deposition area, an initial task is to drive transport tunnels and main tunnels, preliminarily as a tunnel loop according to the explanation in Section 4.5.1, see Figure 4-10. Driving of the tunnels will be preceded by pilot drilling. In general, drilling and investigations are carried out in a similar manner as during construction the ramp and central area, see Section 4.2.1 with Figure 4-2 and Figure A3-3 in Appendix 3. Tunnel mapping is done after each blasting cycle.

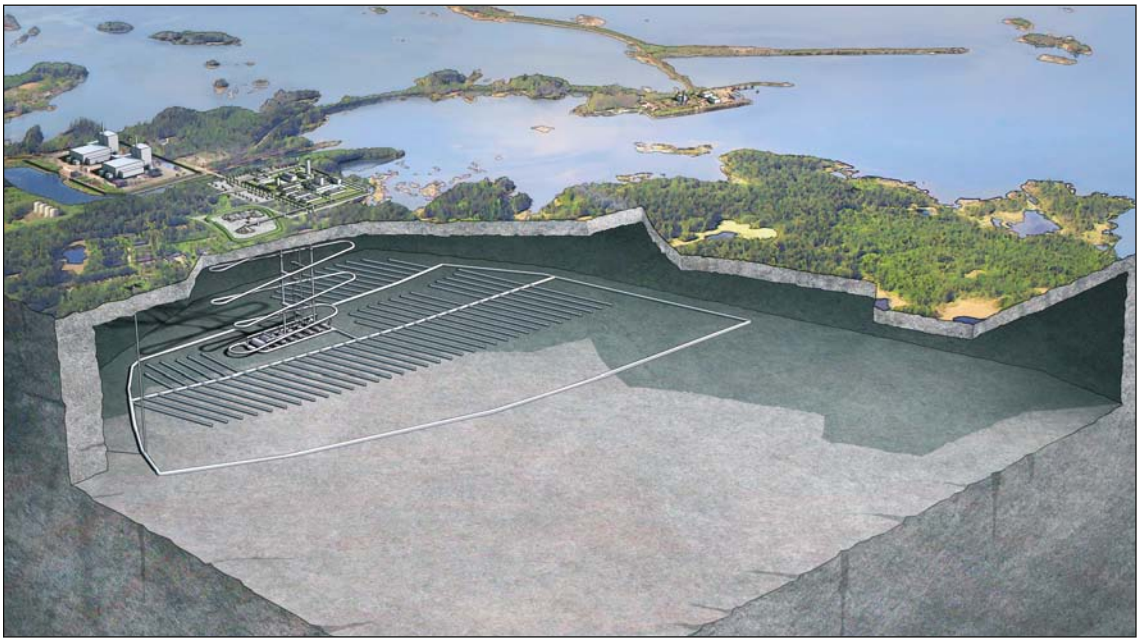


Figure 4-10. The final repository's repository area consists of several deposition areas and will be built out in stages. The figure illustrates the built main tunnel for a new deposition area prior to construction of deposition tunnels within this area.

In addition to these routine investigations in conjunction with the construction of transport and main tunnels, a number of other investigations may be performed, e.g. for bounding and detailed planning of the deposition area. The boundaries of the tectonic lens, as well as the positions and properties of the deformation zones for which respect distances apply, are examples of such issues. How these investigations are to be conducted in a particular deposition area cannot be answered in general but must be determined in each individual case. If standard pilot holes do not provide the necessary information, investigation boreholes extending beyond future underground openings may be considered, provided they can then be plugged satisfactorily so that they will not adversely affect the repository's barrier function.

Depending on their orientations within the deposition area, seismic or radar measurements can be performed from and between the tunnels. Seismic reflection is probably the best method for identification of deformation zones. The penetrating power of the radar waves is limited by the salinity of the groundwater, making radar measurements less interesting for zones at great distances from the tunnel. The applicability of the methods will be studied within the framework of planned method development, see Section 7.3.1.

Some idea of where "large fractures" occur within the deposition area can be obtained in this situation, even though the issue becomes more urgent in the deposition tunnels, see Figure 4-8, diagram 2.

Tunnel mapping furnishes an updated rock type distribution, where the occurrence of thermally anomalous rock types within the deposition area is of primary interest.

Based on results from the routine investigations and from specially conducted investigations in the finished tunnel loop, it should be possible to verify the previous model to some extent, and to define in greater detail the properties of the rock within the deposition area in question, before the construction of deposition tunnels begins.

4.5.5 Detailed characterisation in conjunction with construction of deposition tunnels

When a transport and main tunnel loop has been established, the deposition area with its deposition tunnels can begin to be built out in steps. Each such construction step is planned in detail following the decision sequence and the measures described in Section 4.5.3. The decision mentioned there about location and construction of deposition tunnels consists in turn of two interim decisions. First the positions of the deposition tunnels are determined and pilot holes are drilled and investigated to verify that the rock volume is good enough, and then decisions are made whether these deposition tunnels should be built or not.

Detailed characterisation in connection with detailed planning and construction of deposition tunnels consists of:

- Pilot drilling for deposition tunnels with associated investigations.
- Investigations in conjunction with the construction of a deposition tunnel.
- Investigations of finished deposition tunnel.

Pilot drilling for deposition tunnels with associated investigations

In order to obtain a solid basis for the detailed planning of the deposition tunnels, pilot holes will be drilled from the main tunnel. Pilot drilling is done using ordinary core drilling methodology. It is particularly important that the borehole stays within the periphery of the future tunnel so that parts of the borehole do not remain in the tunnel wall when the tunnel has been driven. Drilling and investigations according to the procedures presented in Section 4.2.1 are planned for these pilot holes as well.

The degree of detail in the pilot holes is so high and the determination of the spatial distribution of the properties of the rock is so good (deterministic) that a relatively good idea can be obtained of how large a fraction of the planned deposition positions can be used. Essential properties are rock type distribution, particularly the occurrence and extent of the subordinate but thermally anomalous amphibolite. It is particularly important to reduce the uncertainties regarding thermal conductivity in the RFM045 rock domain. Supplementary data on thermal conductivity can be obtained if needed by field or laboratory methods, see Section 7.3.4 and Appendix 3 (Section A3.6).

Furthermore, targeted efforts can be made to identify “large fractures”, not just by radar and seismic reflection in individual pilot holes, but also by measurements between pilot holes, known as cross-hole measurements. If the boreholes penetrate a water-conducting formation, hydraulic cross-hole measurements (interference tests) can also be performed, see also Figure 4-8, diagram 3. Studies and development work are being pursued on the possibility of identifying “large fractures” by means of these measurement and modelling methods. The methods will be tested before they are applied in the final repository.

Pilot hole drilling should be carried out well ahead of when the tunnels are to be built. If conductive fractures are encountered, the finished pilot holes can be equipped with packers so that hydraulic responses from the drilling of the subsequent holes can be detected for the purpose of identifying any conductive fractures or fracture zones (extent and hydraulic connectivity) in the rock volume in question. Above all, groundwater monitoring within the deposition area should be carried out over such a long time that it furnishes data for hydrogeological modelling. Such an arrangement is also a prerequisite for performing the aforementioned interference tests.

Investigations during and after construction of deposition tunnel

When results from pilot holes and updated models have verified that a deposition tunnel offers sufficiently many canister positions, a decision is made to build the tunnel. During tunnelling, investigations are conducted in probe holes, and tunnel walls are mapped according to standard procedures (see Section 4.2.1). The requirements on the excavation-damaged zone (EDZ), if any, are strictest in deposition tunnels, especially on the tunnel floor. Some form of follow-up measurement of the properties of the excavation-damaged zone is therefore needed, but a methodology for this has not yet been established.

Since the tunnel geometry and the tunnel’s orientation to the maximum principal stress are of great importance for how stress concentrations occur and thereby for the risk of spalling, the deposition tunnels in the current layout have been positioned nearly parallel to the assessed maximum horizontal stress. The risk of continuous spalling along deposition tunnels and spalling in deposition holes has thereby been minimised. The possible occurrence of spalling will be investigated in the deposition holes as they are finished.

The tunnel floor must be smooth so that deposition of canisters can be carried out efficiently. The tunnel will therefore be built in two steps. First the top heading (the upper and middle part of the tunnel) will be blasted out and then the bench (the lower part). Tunnel mapping will then probably be carried out in two steps. Compared with driving of the ramp, when all activity is concentrated at a single tunnel face, availability for mapping of the deposition tunnels is much greater, since several tunnels are available at the same time. This provides flexibility and an opportunity to choose the most suitable mapping occasion to minimise disturbance of the tunnel works. A suitable plan may be to first carry out a general mapping to document the most important features and then do the complete mapping on a later occasion. The fact that the tunnel face can only be mapped during the period up until the next blast must naturally be taken into account in the planning, along with when the results from mapping and modelling on the tunnel scale need to be ready.

In order for backfilling to be able to be done correctly and result in sufficiently good function being achieved, the geometry of the tunnel must lie within the tolerances specified in the design premises. An initial surveying of the tunnel contour is done in conjunction with tunnel mapping, but this will probably be supplemented to provide updated geometric information for tunnel backfilling.

The total water inflow into the deposition tunnel will begin to be measured as soon as possible after tunnelling. This is done by building a weir at the tunnel mouth and recording the water flow that passes over this weir, in basically the same way as at the Äspö HRL /Almén and Stenberg 2005/. There are also requirements on point measurement of water inflows.

In relation to the pilot holes, tunnel mapping provides an even higher degree of detail regarding the spatial distribution of the properties of the rock. Thermally anomalous rock types (mainly amphibolite) and deformation zones with a risk of instability and water inflows are examples of features that must be mapped with high accuracy.

The occurrence of "large fractures" will once again be investigated, now by e.g. identifying from tunnel mapping whether there are fractures or minor deformation zones that can be followed around the entire tunnel perimeter. Such FPI objects (see Section 2.1.1) comprise a part of the EFPC criterion (see Appendix 1) /Munier 2010/. From the deposition tunnels, tunnel radar and tunnel seismic measurements (possibly also cross-tunnel measurements) can be performed to further verify the occurrence and geometry of "large fractures", now above all beneath the tunnel floor where subhorizontal "large fractures" could intersect several planned canister positions, see Figure 4-8, diagram 4. If this is the case, these positions are disqualified according to the second component of the EFPC criterion. The premises for using seismic vs. radar measurements are discussed in the preceding section, "Pilot drilling for deposition tunnels with associated investigations".

Updated models on detailed scales based on investigation results from the deposition tunnels provide the final basis for a preliminary setting out of canister positions. The thermal conductivity of the rock can decide whether individual canister positions are disqualified. The occurrence of "large fractures" is another factor that serves as a basis for the setting out of canister positions.

4.5.6 Detailed characterisation in conjunction with excavation of deposition holes

When detailed characterisation in a deposition tunnel has been finished as described above and preliminary canister positions have been determined, a couple of steps remain before finished deposition holes can be approved and handed over for deposition of canisters. These are:

- Drilling of and investigations in pilot holes for deposition holes.
- Drilling of deposition holes.
- Verifying investigations in the deposition holes.

Drilling of and investigations in pilot holes for deposition holes

Pilot drilling is carried out at the preliminary canister positions. Like all other pilot drilling, it is performed as core drilling. One pilot hole is drilled per canister position, unless special reasons exist to do otherwise. A basic programme of investigations is executed in the pilot holes which is preliminarily the same as that applied in the other, much longer pilot holes. However, the short length may limit the number of applicable methods. The choice of these methods is one of the technical matters that will be examined in the upcoming planning work.

Borehole mapping is done in great detail with regard to those features that are essential for long-term safety and that have also been of primary interest in the preceding investigation steps, namely fractures, rock type distribution and the occurrence of the subordinate rock type amphibolite with anomalous thermal properties. Furthermore, hydraulic tests are performed in the pilot holes to identify and characterise conductive fractures that intersect the pilot hole. Indications of "large fractures" according to the EFPC criterion are of particular interest, whereby modelling is done on detailed scales by co-interpretation of information from other pilot holes and from previous seismic and radar measurements from the tunnel floor. If necessary, additional radar and seismic measurements can be performed from the pilot holes and possibly also between pilot holes, see Figure 4-8, diagram 5. If water inflows occur, other hydraulic interference tests can also be applied to identify and characterise a "large fracture", if it has such an orientation that it can intersect several pilot holes. Packers may need to be installed in the pilot holes for this purpose.

According to the design premises, the water inflow to a deposition hole may not exceed a given stipulated value (Appendix 1). Measured water inflow to the pilot hole is used to determine whether the design premises will be met.

Drilling of and verifying investigations in the deposition holes

Based on the results from pilot holes and updated models, it must be verified that the preliminary canister positions have the required properties. If so, a decision can be made to drill deposition holes in these positions. Such a decision will probably apply to several deposition holes, which will be drilled in the same drilling campaign. For an account of how drilling of deposition holes is done, see the Design and Construction Report /SKB 2010a/. In some cases it may be advantageous to record pressure responses in nearby pilot holes during drilling, preferably with packers fitted in them.

Investigations in the deposition holes (Figure 4-8, diagram 6) will document the geoscientific conditions for the purpose of finally verifying whether the design premises for deposition of canisters are fulfilled. Geological mapping of the borehole wall will be done with a methodology that has not yet been determined in detail, but can be described a cross between core mapping (Boremap, see Appendix 3, Section A3.4) and shaft mapping. It is thereby particularly important to observe any tendencies towards spalling. The possible indication of a "large fracture" according to the EFPC criterion will be investigated once again.

The inflow to a finished deposition hole can now be measured and compared to the design premise. Measurement equipment can then be installed to record the inflow until deposition is done, when final verification can be made whether the inflow requirement is met.

The geometric requirement on the deposition holes can be checked by some form of measurement system (e.g. laser scanning or total station) that has not yet been specified.

Final approval of deposition holes – continued buildout and documentation of the initial state of the entire final repository

After investigations in the deposition holes have been finished and models have been updated, a final decision can be made to approve deposition holes for deposition of canisters. At this time, final documentation of deposition tunnels with approved deposition holes can be issued. Excavation of additional deposition tunnels will then continue in this manner in one construction phase after another until all the deposition areas are finished, and finally until the entire repository area is built out and all spent nuclear fuel has been deposited. The final documentation of the underground openings in the entire facility, including any excavation-damaged zones (EDZs) around these openings, comprises the initial state of the final repository for the safety assessment's calculations of long-term safety.

4.5.7 Other investigations in the repository area

The detailed characterisation programme for the repository area that is proposed in Section 4.5 has been structured according to the sequence in which construction is carried out within a deposition area. As in the case of accesses and the central area, it is additionally foreseen that special investigations of various kinds will be conducted within the repository area. These include investigations to verify the properties of the rock that it is more suitable to carry out separately from the construction sequence. For example, deposition tunnels can be made available for tests, sampling or attempts to resolve questions or uncertainties. Conceivable examples are hydrogeochemical sampling, hydraulic cross-hole tests, thermal experiments etc on suitable scales. These investigations will mainly be initiated based on the needs of the safety assessment. A need for investigations is also foreseen in connection with integrated testing prior to the start of operation. The main purpose is to fine-polish methodology and interaction with other parts of the construction process during operation.

4.6 Supplementary investigations for the purpose of assessing repository safety

The information that is gathered during the construction process will also comprise the most important basis for assessment of the final repository's long-term safety. In addition, supplementary investigations may be needed to obtain further data for safety assessment. The investigations mentioned in Section 4.5.7 belong mainly to this category. Investigations may also be called for in the rock volume outside the repository or to determine conditions in the recipient for radionuclide transport from the repository. Such investigations may also be performed from the ground surface.

Supplementary investigations are initiated in response to safety evaluations and safety assessments.

5 Quality control and quality assurance of detailed characterisation

SKB's activities are governed by an overall company-wide management system. This system contains both Group-wide and activity-specific procedures. Prior to and during the site investigations at Forsmark and Oskarshamn, SKB carried out an extensive project involving development and improvement of its quality system for field investigations and modelling. The system was gradually refined during the entire site investigation phase as new experience was obtained.

A relatively extensive overhaul of SKB's management system is foreseen prior to detailed characterisation, including the quality system for investigations and modelling. The purpose is to satisfy the quality requirements on data and reporting that will be made due to the fact that the final repository is a nuclear facility.

Detailed characterisation is integrated with design and construction in both execution and use of results. The documentation from the detailed characterisation will comprise part of the total documentation for the final repository, which describes e.g. the initial state of the facility's underground openings and surrounding rock volumes. This leads to the need for an integrated quality system for detailed characterisation, design and construction based on SKB's company-wide management system. The presentation in the present chapter is, however, concerned exclusively with detailed characterisation and the final repository's construction phase. Activities during the operating phase will conform to quality procedures within a management system that will then have undergone a thorough overhaul.

5.1 Quality aspects

Fundamental quality aspects can, like during the site investigations, be expressed as "doing the right things" and "doing things in the right way". The first refers to what detailed characterisation is supposed to do, i.e. what information is supposed to be gathered. The right information is obtained via the detailed characterisation programme that will gradually be developed up until the start of construction, of which this report comprises a first version. Internal and external review of the programme will ensure that the established quality goals are achieved.

The second fundamental quality aspect is that things should be done "in the right way" and with sufficient documentation to satisfy established requirements on traceability. This relates to the control down to the detailed level which SKB will exercise for the execution of detailed characterisation, with an emphasis on how methods are to be executed within process- and project-driven activities. Project plans, activity plans and method descriptions constituted important steering instruments during the site investigations. Equivalent steering documents will be prepared or updated for detailed characterisation.

Some examples are given below in point form of other aspects that are of importance for the quality system that will be developed for detailed characterisation.

- Compliance with the requirements in SSM's regulations, regardless of whether it is a question of SKB's own efforts or work done by outside suppliers.
- Clear division of powers and responsibilities (a prerequisite given that a large number of actors will be involved in the construction of the final repository).
- Procedures for supplier assessment and selection, based on such aspects as the supplier's own quality system with associated self-inspection and documentation.
- Systems and procedures for quality audit.
- Use only of pre-approved and fine-adjusted methods.
- In-service training of both own personnel and outside suppliers to achieve established quality goals.
- Make personnel aware of the role of their own job in the quality chain and its importance for the quality of the end product.

Contractors must routinely quantify uncertainties in primary data. Similarly, uncertainty estimates are an essential part of the modelling results. An important tool for structured assessment of confidence and remaining uncertainties linked to primary data, models and model results is the type of workshops held within the framework of the site investigations, see for example /SKB 2008b/.

5.2 Steering and quality assurance

In contrast to the site investigations, when the actual investigation part was the main activity, detailed characterisation will comprise a support activity to design, construction and safety assessment, which can thus be said to suborder the investigation work. Certain investigations will be conducted in project form, while other, more routinely and frequently recurring investigations will be carried out as processes. In the case of both investigations and modelling, method descriptions and project plans comprise important steering documents for production and handling of primary data and for execution of modelling and further processing of modelling results.

The steering documents used during the site investigations will serve as a basis for establishing relevant procedures and appropriate steering documents for detailed characterisation.

5.2.1 Control of data quality

During the site investigations, SKB developed methods for quality control of delivered data. An important step in the work of increasing the quality of data deliveries and obtaining efficient data flows ("right from the start"), as well as to improve quality assurance in general, has been the introduction of method-specific delivery control plans (DCPs). In these, the quality-critical elements of the method are emphasised and random spot checks of data deliveries are routinely performed. A general check concerns quality control of the supplier and ensuring that his self-inspections are reported in a signed checklist.

Prior to detailed characterisation, quality control of data will have to be adapted to the premises, requirements and conditions that will prevail in this phase. This applies in particular to the process-oriented ongoing activities, where checks of data and model analyses must be performed quickly and efficiently, since quality-assured results of this type are important for the ongoing building process.

5.2.2 Documentation and traceability

Large quantities of data are generated and handled during construction and operation of the final repository. In most cases the data are used in a number of analysis and evaluation steps, where results from one step are used as input to the next step, etc. To permit efficient identification, readout and utilisation of relevant primary data from established databases, it is necessary, given the large quantities and variety of data, to make high demands on the choice of database format as well as the forms of result presentation.

An important basic principle for achieving the necessary control and traceability in the whole chain is that adequate documentation of input data, process (execution of the activity) and output data is achieved, where:

- Input data are unambiguously identified.
- The process/activity is precisely defined and documented.
- Output data are unambiguously identified.

Traceability in accordance with the needs of the Observational Method is ensured by consistently executed documentation in all steps.

The process survey described in Section 3.4 provides a basis for the construction of an optimal system for documentation and traceability for detailed characterisation.

5.2.3 Plausibility check of data

Once the quality of the primary data has been assured, a number of checks remain that have a bearing on the plausibility of the data and also focus on direct or indirect support in the data for relevant conceptual and descriptive site descriptive models. The first type of check entails verifying that the magnitude of a data value is compatible with its experiential range of variation. The point of reference at the start of the detailed characterisation is the database established during the site investigations, which will then gradually be enlarged as detailed characterisation proceeds. Once the plausibility of the data has been established, they can be grouped and investigated conceptually by different forms of coplots in two or three dimensions. Furthermore, the plausibility of processes that act over time should be checked.

5.3 Quality assurance of models and modelling results

As with quality assurance of primary data, the point of departure for achieving good quality assurance in modelling results is to have a broad perspective so that high quality is created in the whole chain from definition of modelling task, choice of modelling tool and supplier (modeller/model team/company), activity plans and service contracts to audits, delivery inspections and entry in SKB's model databases. The presentation in the next section mainly concerns numerical models. Future programme reports may need to also shed light on quality assurance of descriptive/conceptual models, see Section 3.2.

5.3.1 Verification of code and results

A prerequisite for verification of the results of quantifying modelling is that the results have been documented in a reliable fashion. Another prerequisite is that reliability of the modelling tool has been ensured by verifying the modelling code for a given simple physical problem in relation to a known and accepted analytical solution. This verifies that the numerical code is utilising the right fundamental equations, and that they are being applied correctly. However, this verification is not sufficient; there is also a requirement that the contractor must have documented knowledge and experience of the code in question, primarily from applications related to the problem at hand.

5.3.2 Documentation and traceability

Experience from the site descriptive modelling at Forsmark and Oskarshamn indicates that it is possible to create good traceability and efficient management of modelling tools (versions), basic datasets for quantifying calculations (geometry, material properties and boundary conditions, see Section 3.2) and results (versions and alternatives). These datasets are specified and output data files/plots are given unique names that permit tracing of model alternatives and associated datasets.

There is, in spite of this, still room for improvement. For example, the documentation associated with a given simulation or model calculation could also include a log describing goals, input data and changes in the model, e.g. of geometry, material properties or boundary conditions as well as output data/results.

6 Reporting of results from the detailed characterisation programme

Construction and operation of the final repository for spent nuclear fuel will require extensive reporting in the form of facility documentation, safety assessments, decision documents, technical and geoscientific reports etc for both SKB-linked and outside users and interested parties. Detailed characterisation will furnish some of the factual basis for this reporting.

The scope and forms of different types of reports will be governed by the overall reporting needs in connection with construction and operation of the final repository and by the specific reporting needs of the detailed characterisation programme. Above all, however, the format for reporting to design and construction must be developed so that deliveries are efficient and effective.

6.1 What should be reported?

The bulleted list below exemplifies results and documents that will be produced related to the detailed characterisation programme, and for which some form of reporting will be required:

- Investigation data (primary data and processed data).
- Modelling results (including predictions and important intermediate steps).
- Monitoring data (for characterisation and assessment of environmental impact).
- Steering documents (e.g. method descriptions and activity plans, quality plans and control plans), see Section 5.2.
- Decision documents.
- Documents that relate to communication between different actors within the project (e.g. minutes from building meetings and other meetings).

6.2 When and how should reporting be done?

Reporting of the results of detailed characterisation should generally be tailored to what is needed for construction and operation of the final repository, but also so that it meets more immediate and short-term needs during ongoing activities. In both cases, besides being technically and scientifically adequate with regard to contents and quality, the reporting should also be tailored to the needs of different users.

Important geoscientific/technical reporting occasions are, for example, in conjunction with the planning and detailed adaptation of a facility part, including associated pilot holes and tunnels. Another important example is reporting of the results of detailed characterisation in the form of site descriptive models in conjunction with the updating of the Safety Assessment Report with constituent safety assessments.

As far as primary data and models of different kinds and for different purposes are concerned, storage in primary databases and model databases, model visualisations and presentations in reports will be carried out in compliance with the control documents that will be prepared, see also Chapter 5.

Construction and operation of the final repository are activities that will take place over a long period of time, and reporting of investigation and modelling results will therefore be done at regular intervals. For example, during the construction of accesses it may be appropriate to allow specified tunnel lengths to determine when routine overall reporting takes place, even though preliminary reporting of results from probe holes and general tunnel mapping (between blasting rounds) is done on an ongoing basis. Since the results of investigations and modelling, according to the principles of the Observational Method, will be used to control the construction process, detailed characterisation results need to be quality-assured and delivered to keep pace with this need. Based on these recurrent data deliveries, geoscientific and technical reports of various kinds will be compiled at varying intervals and presented for a specific purpose and on a relevant scale.

SKB has its own experience of reporting of underground activities from the construction of the Äspö HRL, when:

- Tunnel mapping etc was documented on a daily basis (for each blasting cycle), see also Appendix 3.
- Systematic reports covering 150 m of tunnel length were produced within three disciplines: 1) geology, 2) hydrogeology/hydrogeochemistry and 3) rock quality and rock support.
- More exhaustive reports including 1) geology and rock mechanics, 2) hydrogeology, 3) groundwater chemistry and 4) transport properties were produced after every 750 m of tunnel length.

Similar reporting could conceivably occur during the construction of the final repository, but with a stronger focus on speed and integration between different disciplines.

It is of great value to have a robust and user-friendly reporting and storage system for the large quantities of internal decision and quality documents that will be produced within the framework of the detailed characterisation programme. The handling of activity documents during the site investigation phase can provide guidance, but probably needs to be further developed to cope with the much larger number of documents expected during the final repository project.

How reporting is to be done in different cases, e.g. in terms of documented quality assurance, traceability and time perspective for preservation, will be planned in consultation with the users during the coming years up to the start of construction.

7 Continued planning and development

This chapter provides a summary of the continued planning and development work for detailed characterisation before and during the construction of the final repository at Forsmark. The background to and reasons for these activities are presented in preceding chapters, mainly Chapters 3, 4 and 5. The following subjects are discussed in the present chapter:

- Continued development of the detailed characterisation programme.
- Further development of modelling strategy, methodology and tools.
- Further development of methods and instruments for investigations.
- Further development of methods and equipment for data handling and data storage.

Preliminary ideas for development of quality programmes as well as steering and reporting documents applicable to the detailed characterisation phase are presented in Chapters 5 and 6 and are not dealt with further in this chapter.

The main timetable for realization of the final repository is presented schematically in Figure 1-2. Based on this timetable, two milestones have been identified for overall time management of the planning and development work for the detailed site characterisation. These milestones are:

- **Prior to start of construction:** A programme for detailed characterisation during construction of the final repository's accesses must be completed and presented in a programme report. Furthermore, tools to be used for this must then be fully developed and have undergone final testing.
- **Prior to the start of tunnelling within the repository area**: A programme for detailed characterisation during excavation of deposition tunnels and deposition holes must be completed and presented in a programme report. Furthermore, tools to be used for this must then be fully developed and have undergone final testing.

7.1 Continued development of programme for investigations and modelling

The framework programme will be examined in connection with the licensing review of SKB's application under the Nuclear Activities Act. The programme will then be updated with a focus on detailed characterisation during the construction of accesses to the final repository. Methods and instruments will have been further developed for this programme. This will be followed by progressive updates of the programme with a specific focus on other facility parts, i.e. central area and deposition areas, as the construction of the repository evolves.

The continued work of determining the information need will proceed in parallel with further development of modelling strategy, methodology and tools, see Section 7.2. Before the information need is finally established, a cross-check will be made against the conclusions in the SR-Site safety assessment /SKB 2011/, as well as against the conditions that may be linked to the licence to commence construction of the final repository.

7.2 Modelling – further development of strategy, methodology and tools

The general status of modelling at the time of completion of the site investigations at Forsmark is described in Section 3.2 and Appendix 2. The manner in which new data from detailed characterisation are intended to be used in future modelling is also described, with a special focus on applicable design premises. It can be noted that even though several years remain until the actual implementation of the detailed characterisation programme, there is a need to try out certain modelling methods and tools in a realistic situation within a couple of years. Possible applications include the construction of a planned new tunnel at the Äspö HRL and at Posiva's underground facility ONKALO at Olkiluoto. Before these applications can be realized, however, some fundamental work remains to be done. With this in mind, general needs linked to the development of methodology and modelling tools are identified in the following.

7.2.1 Modelling – strategy and methodology

For the continued planning work it is important for all disciplines to identify, formulate, substantiate and document updated methodology, based on the needs of different users. To make this possible, an overall modelling strategy must be established that both covers all disciplines and takes important integration aspects into account, everything from continuous modelling during construction to periodic updating of the site descriptive model for safety evaluation/safety assessment. This integrated strategy should result in a good overview of interdisciplinary analysis linked to important design premises, e.g. regarding positioning of deposition holes in relation to the EFPC criterion and criteria linked to allowable water inflows. Further, separate strategy descriptions should be established for individual disciplines, since these entail a flexibility that facilitates modifications. The overall modelling strategy can thereby be kept up to date in an efficient manner.

The strategies and discipline-specific methodologies applied at Forsmark at the end of the site investigation phase will, with necessary additions linked to the underground aspects, also be applicable to the preparation of site descriptive models related to future safety evaluations and safety assessments. However, before the operating phase is commenced, there is a need for an updated, clear description of the strategies and methods that will be used in the modelling work. It is important that the description should clarify differences in content, approach and scope between different disciplines and facility parts.

Table 7-1 presents specific issues that will be the subject to continued method development within the framework of the detailed characterisation programme. These issues are directly or indirectly linked to the design premises or prompted by the data need during construction and operation. An overall timetable for the planned development work is shown in Figure 7-1.

7.2.2 Modelling tools

Most modelling tools that will be needed are already today available, or almost available. However, some reservation must be made for the capability of the tools to fully utilise new types of underground information. The continued work mainly involves identifying, substantiating and documenting planned modelling tools in relation to new components in the dataset and to the differentiated strategies and methods discussed above.

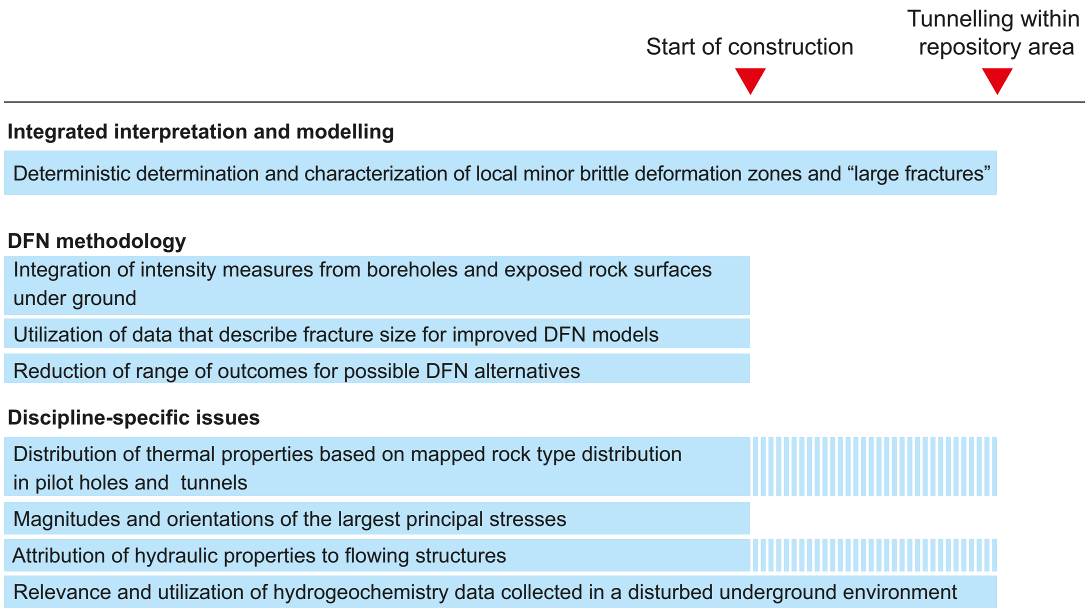


Figure 7-1. *Overall timetable for development of modelling methodology. The development activities are controlled so that the methods are ready well in time before the start of construction or tunnelling in the repository area, respectively.*

Table 7-1. Summary of important modelling issues that are subject to continued development work within the framework of the detailed characterisation programme, see also Appendices 2 and 3.

Issue	Description, available data and explanation	Development plans
Geology/Hydrogeology: Deterministic determination and characterisation of "large fractures" that can occur in the rock around the deposition tunnels. Modelling (prediction), conditioning/ verification of models "large fractures" (linked to the EFPC criterion and criteria relating to hydraulic properties). Positioning of deposition holes.	New data come from geology/ geophysics, recording of pressure/ flow during drilling and possibly from interference tests (mainly in deposition areas).	Overhaul of methods for interpretation of results from geophysical surveys, interpretation of hydraulic boundaries and size/length of active hydraulic structures and integrated interpretation/modelling, including scaling of fracture properties to relevant scales. Development of methodology for integrated interpretation of geological and hydraulic information collected in a single borehole (single-hole interpretation) and in a single tunnel or tunnel/shaft interval (single-tunnel interpretation).
Geology: Integration of data from underground boreholes and rock surfaces. The methodology should be devised for combining this information to an improved DFN description.	Integration of measures of intensity, fracture orientation and fracture trace length from boreholes and tunnels/ shafts.	Establishment of methodology after systematic review of relevant existing data from e.g. Äspö and ONKALO.
Geology/Hydrogeology: Utilisation of data that describe fracture size for improved DFN models.	New data come from mapping of ramp, shafts and tunnels. Allows measurement of fracture size on exposed rock surfaces over great distances (including between tunnels).	Besides an overhaul of mapping methodology, a review is needed of methodology for bringing imaging of mapped tunnel surfaces to a 3D representation in relevant models.
Geology/Hydrogeology: Reduction of range of outcomes for possible DFN alternatives.	The site descriptive modelling at Forsmark and Laxemar generated a large number of alternative DFN model parameterizations that proved impractical to include in uncertainty and sensitivity analyses. The extremes here are utilisation of a few alternatives with great uncertainties, or several more limited alternatives with smaller uncertainties.	Development of methodology that identifies how new data can be utilised for improved limitation of the range of outcomes. Alternative models preferably reflect conceptual uncertainty, while variances point to other uncertainties. An obvious step is integrated analysis of geological and hydrogeological information for the purpose of arriving at an integrated DFN model.
Thermal properties: Distribution of thermal properties based on mapped rock type distribution in pilot holes and tunnels.	Detailed tunnel mapping of rock types permits a virtually deterministic description of the distribution of thermal conductivity.	Development of methodology for continuous translation of rock type mapping and adaptation to a suitable scale. Support from verifying measurements on a larger scale is important, see Section 7.3.4.
Rock mechanics: Magnitudes and orientations of the largest principal stresses.	New data come from convergence measurements (tunnel) and borehole measurements under ground.	Development of methodology for efficient inverse modelling of convergence data and data from determination of Young's modulus. Consideration of experience from Posiva's extensive analyses of convergence data, overcoring data and data from hydraulic rock stress methods on different scales.
Hydrogeology: Attribution of hydraulic properties to flowing structures	New data come from mapped flowing structures observed in underground openings, supported by information from pilot and probe boreholes.	Need for methodology for quantification of properties (transmissivity). Necessary allowance for scale effects, two-phase flow and skin. Cf. experiments in Stripa and Äspö HRL.
Hydrogeochemistry: Relevance and utilisation of hydrogeochemistry data collected in a disturbed underground environment.	Sampling in a near-tunnel environment requires an understanding of the geological and hydrogeological situation and progressive changes in this situation.	Review of experience from Äspö and ONKALO and formulation of methodology for integrated interpretation and utilisation in hydrogeochemical and hydrogeological modelling.

7.2.3 Reporting

The progress made in the area of modelling will constitute an important part of the detailed characterisation programme's development in the years to come. Future programme reports offer good opportunities to present the results of the development work.

7.3 Further development of methods and instruments for investigations

Against the background of the compilations of the parameters to be determined during the detailed site characterisation and based on the current status of methods and instruments, SKB will prepare a plan of action for further development of investigation methods and instruments. This will, as in the case of model development, be described in future programme reports.

Method and development activities that are known today and judged to be urgent are presented in this section. In certain cases, development work and performance testing should be completed before the rock works are begun. For other methods and instruments, the need for duty-proven and fully operational systems lies further ahead in time, mainly when tunnelling in the repository area commences. No crucial difficulties are expected in the development work considered thus far. The importance of allocating sufficient time and resources for final inspection and performance testing before planned use in a production context should be emphasised, however.

The point of departure for this section is the presentation of methods and instruments provided in Appendix 3. An equivalent presentation of development needs and plans can be found in somewhat abbreviated form in /SKB 2010b/. A summary of the development initiatives that currently have top priority, along with an assessment of when the development work should be finished, is provided in Figure 7-2.

Knowledge and experience gained from investigations in conjunction with other underground projects will be studied as a part of the preparations for start of construction. As mentioned in Chapter 3, Posiva's ongoing tunnelling for a final repository in Olkiluoto, Finland, is of particular interest, since the issues related to long-term safety are the same there as in SKB's final repository project. SKB and Posiva also plan to collaborate on the development of instruments and methods in a number of areas. Ongoing tunnelling works in the Stockholm area, as well as underground projects in other parts of Sweden and other countries, can also provide important experience.

7.3.1 Mapping and other investigations of underground openings

Mapping of tunnels and shafts

The geological documentation of the underground openings of the final repository will require a tunnel mapping system that meets high standards with regard to quality of results, robustness and user-friendliness. The development of such a mapping system, known as the RoC system (*Rock Characterisation System*), has been initiated. The system is based on the principle of creating a digital mapping record by photogrammetric means, after which the information from the actual mapping is entered into a field computer which the mapping geologist brings along on each mapping occasion (see Section A3.10 in Appendix 3). The development work, including tests at the Äspö HRL, is planned to be finished in good time before the start of construction.

Characterisation of "large fractures"

Identification and characterisation of "large fractures" is a priority task for detailed characterisation, since such fractures can disqualify canister positions. According to the EFPC criterion /Munier 2010/, a deposition hole intersected by a "large fracture" that can be followed around the full perimeter of the tunnel should be rejected. In the event a "large fracture" intersects at least five deposition holes, they should also be rejected (see also Appendix 1 and Figures 2-2 and 4-8).

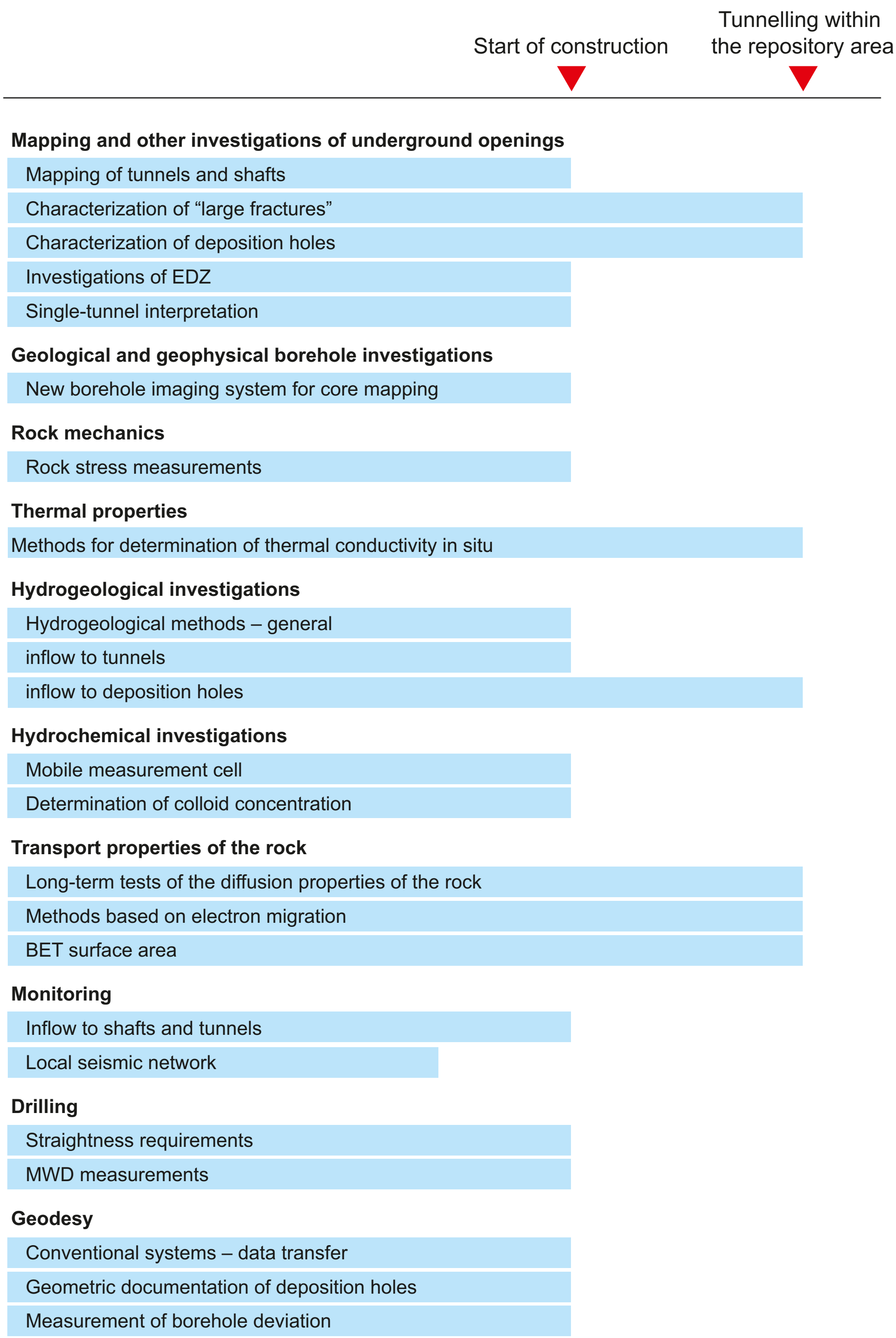


Figure 7-2. *Overall timetable for development of investigation methods and instruments. The development work is managed so that the methods are ready well in time before the start of construction or tunnelling in the repository area, respectively.*

In addition to the geological mapping methods for tunnels and boreholes, a combination of geophysical and hydraulic methods probably has to be applied for identification and characterisation of "large fractures". The basic methods are established, but some upgrading is required, and methodology for co-interpretation of measurement data needs to be devised.

A knowledge of which properties of fractures (e.g. mineral fillings) can be determined by different measurement methods is fundamental for the characterisation of "large fractures". /Cosgrove et al. 2006/ did a literature study of the possibility of identifying and characterising fractures in different types of bedrock based on their properties and origin. However, further studies are needed of the link between properties and geophysical anomalies of various kinds for fractures in crystalline bedrock, which geophysical methods are most effective for fracture detection and characterisation, and which line of technical development appears most fruitful in this area. This work has been initiated and is being pursued partly in cooperation with Posiva. The final results will not be applied until the first deposition area is built, but since the question is of great importance, the technology probably needs to be tested and fine-tuned for several years before it can be considered to be ready for routine use.

Characterisation of deposition holes

A total of 6,000 deposition holes will be drilled, investigated and approved in the final repository. Characterisation will take place in two steps. First a pilot borehole, which can be investigated using basically the same methodology as other cored boreholes, is drilled. However, some existing probes are too long for use in deposition holes and may have to be modified.

Once a deposition hole has been drilled, the borehole wall is mapped with respect to rock type distribution and character and the occurrence of ductile and brittle structures. For this purpose the technology for rock mapping of tunnels will be further developed and adapted for application in deposition holes. Scaling down from tunnel to deposition hole requires considerable development in order for photogrammetry to be used. In addition to ordinary geological mapping, the surface structure of the borehole wall will be thoroughly documented. It is particularly important to observe tendencies towards spalling and to once again investigate the possible occurrence of "large fractures".

Characterisation of deposition holes lies relatively far in the future, but method development has already begun in the Äspö HRL and will be pursued further.

Investigations of EDZ

An investigation is being conducted in cooperation with Posiva regarding what study methods have the best potential for characterising the EDZ (see Section 4.5.2). The main non-destructive investigations for characterisation of the EDZ that are being considered are based on geophysical methods (high-frequency seismic and radar reflection). Use of *Ground Penetration Radar* (GPR) is also included in the development work. An evaluation is currently under way of an experiment conducted by Posiva, where a combination of GPR and a special form of hydraulic testing has been applied in small-diameter boreholes for characterisation of the EDZ. The results could lead to a new strategy for this type of investigations.

Single-tunnel interpretation

Methodology and forms of presentation for compilation of all data from a tunnel (including pilot boreholes) and its near-field have not previously been systematically applied in SKB's activities, even though the tunnel documentation in the Äspö HRL can to some extent be characterised as single-tunnel interpretation. Experience is also available from Posiva's programme in ONKALO. The methodology must be concretized and further defined in the continued planning work and must be ready when driving of the ramp and shafts begins.

7.3.2 Geological and geophysical borehole investigations

Digital borehole imaging has been used for a long time as a basis for core mapping by means of the Boremap method (see explanation in Appendix 3, Section A3.4). Progress in electronics has been rapid in recent years, and SKB's present-day borehole imaging system, BIPS, needs to be replaced and the Boremap method updated.

A special aspect of a new borehole mapping system that should be considered is its capacity to carry out well centred measurements in deposition holes (diameter 1.8 m) with good resolution of the TV image. For the purpose of increasing the amount of information in Boremap mapping, TV logging could be combined with logging via an acoustic televiewer.

7.3.3 Rock mechanics

One of the most important remaining uncertainties in the site descriptive model for Forsmark concerns the properties of the stress field, primarily the magnitudes of the horizontal stresses. The planning work for further investigations includes identifying the method combinations that have the greatest potential for reducing the uncertainties.

When shafts and tunnels begin to be driven, convergence measurements will be employed as a complement to borehole measurements using hydraulic methods and overcoring. In preparation for convergence measurements at Forsmark, the convergence measurements and analyses being done by Posiva in ONKALO are being studied.

Three methods – the SLITS method plus the LSG and LVDT methods – are under development in cooperation between SKB and Posiva. In the event of a successful outcome, all three methods will be applied at the final repository. The SLITS method (*SLim Borehole Thermal Spalling*) is based on the fact that heating of a rock volume around a loaded borehole within one to two weeks can give rise to an additional load, leading to spalling. The method has potential to become a way to determine the orientation of the maximum primary stress.

The LSG (*Long Strain Gauges*) and LVDT (*Linear Variable Differential Transformer*) methods are special overcoring methods where determination of the stress field is performed on a larger scale (longer transducers and larger diameter boreholes) than in the case of conventional overcoring methods, see description in Appendix 3, Section A3.5. Posiva has employed the methods in one and the same instrument setup, known as the *LSG-LVDT concept*. SKB plans to calibrate the method against known conditions in the Äspö HRL.

7.3.4 Thermal properties

There is a need to develop field methods for characterisation of the bedrock's thermal conductivity that are more rational and less costly than today's. SKB has considered some alternative methods for determining the thermal conductivity of different rock types in situ and on a scale that is relevant for the canister. The development need is difficult to judge at present, however, and SKB is currently awaiting recommendations from a working group under the ISRM (*International Society of Rock Mechanics*), in which a representative from SKB is participating and which is supposed to devise a methodology for determination of thermal properties.

7.3.5 Hydrogeological investigations

Hydrogeological methods – general

SKB has a number of hydrogeological methods at its disposal for use both on the surface and under ground. A priority task in the planning of the detailed characterisation is to select the investigation methods that will be used under ground. Two criteria are crucial. Firstly, the hydraulic tests must meet stringent requirements on measurement accuracy, and secondly, rational logistics and flexible adaptation to other ongoing activities must be achieved. The bedrock at Forsmark is characterised by high hydraulic conductivity near the surface, while very low conductivity is prevalent at repository depth. These extremes can make special demands on the measurement methods.

SKB plans to use a combination of outflow tests, injection tests, flow logging and interference tests. Feasibility studies will be initiated to determine the testing methods and combinations of methods that appear optimal in terms of quality and investigation logistics. Requirement specifications will be prepared for equipment and evaluation methodology will be established. This will be followed by technical development, where deemed necessary.

Inflows to deposition holes and tunnels

Special development initiatives are planned for methods for measuring the small inflows that are expected to occur to pilot holes for deposition holes and finished full-face deposition holes. Development of methods for measuring small seepage in tunnels is also planned. This work will be pursued partly in cooperation with Posiva.

7.3.6 Hydrogeochemical investigations

Most hydrogeochemical field and laboratory methods that SKB has at its disposal meet the requirements of detailed characterisation on quality and functionality. However, development needs have been identified in two areas, which are commented on below.

Mobile measurement cell

Appendix 3, Section A3.8, gives an account of the mobile measurement cells which SKB has used in its work thus far for online and underground measurements of the parameters Eh (redox potential), pH, groundwater temperature, EC (electrical conductivity) and dissolved oxygen. Well functioning equipment will also be needed in detailed characterisation for *online measurements* of these parameters, inside or outside the borehole.

Three alternative equipment variants, each with different development needs, are being considered:

1) *The Borehole Chemmac unit* offers an optimal solution because measurements are made in situ, i.e. under the pressure and temperature conditions that prevail in the sampling section. However, the equipment is primarily intended for use in boreholes drilled from the ground surface, which means it has to be modified for use under ground.
2) *The portable measurement cell* for measurement of Eh, pH and groundwater temperature developed by SKB for the Prototype Repository at the Äspö HRL has certain advantages, even though measurements are not made in situ, since the electrodes are located outside the borehole. If this equipment is the preferred choice, it should be provided with electrodes for measurement of dissolved oxygen and electrical conductivity. Some software development is also needed for handling of measurement data.
3) The third alternative is to *follow the technical development of electrodes and measurement electronics* on the commercial market and, provided electrodes adapted to high pressures and otherwise in compliance with SKB's requirements on quality and robustness should become available, purchase such equipment and, if necessary, make the necessary technical modifications so it meets all the requirements of detailed characterisation.

Determination of colloid concentration

Determination of colloid concentration in groundwater samples has proved to be far from simple. Several methods have been used: 1) filtration in an argon atmosphere through a series of filters with decreasing pore size and ICP (*Inductively Coupled Plasma*) analysis of filter samples, 2) fractionation/ultrafiltration in an argon atmosphere through special filters with a *cut-off* of 5,000 D (Daltons) and 1,000 D, and ICP analysis of the different fractions, 3) analysis of filters by *Scanning Electron Microscopy*(SEM), and 4) the LIBD method (*Laser Induced Breakdown Detection*), which has been used both *online* on water flow directly from boreholes and on in situ samples from steel containers that preserve the pressure from the borehole section. However, no method has emerged as being completely unambiguous and problem-free.

The above methods measure the concentration of the colloids and provide some characterisation of their properties. Determining the quantity of colloids is probably sufficient for the purposes of detailed characterisation. A technique for this that has so far only been used in the laboratory, *single particle counting*, could possibly be further developed for field conditions. However, an initial study is needed to determine if this type of instrument and method can be employed for the groundwater types in question, and how.

7.3.7 Transport properties of the rock

Long-term tests of the diffusion properties of the rock

The discipline includes both field and laboratory methods. Only minor development needs have been identified. Further development is planned of the LTDE concept (*Long Term Diffusion Experiment*) for determination of diffusion and sorption properties in situ based on results from the recently concluded single-hole LTDE-SD experiment at the Äspö HRL /Widestrand et al. 2010/

Methods based on electron migration

Development work has been done on electron migration as a laboratory method for determination of matrix diffusivity using nonsorbing tracers /Löfgren et al. 2009/ as a complement to through-diffusion measurements. Further development of the method is planned for determination of sorption coefficients and matrix porosity on whole rock pieces. A possible in situ application of the methodology for determination of matrix diffusivity will also be investigated.

BET surface area

A new variant of laboratory determination of inner surface areas (known as the BET surface area) is under development and could become a new standard method. This method quantifies the integrated surface area linked to the porosity that is available for sorption in the intact matrix rock.

No or little development need is foreseen for other methods.

7.3.8 Monitoring

Inflow to shafts and tunnels

When underground openings become accessible, the monitoring will be broadened to include the inflow of groundwater to different tunnel sections. Traditional technology will be used for this, but certain improvements are foreseen. In preparation, experience from the fine sealing project at the Äspö HRL /Funehag 2008/ and results from ongoing BeFo projects will be studied and evaluated.

Local seismic network

SKB is considering installing a local seismic network at Forsmark. The purpose is to, in connection with the construction of the final repository, continuously record natural as well as induced seismic activity of considerably lower magnitudes than those that can be recorded in the national seismic network. It will be possible to record both natural earthquakes and blasting rounds. Not only can a database of earthquakes be built up, measurement data can also be analyzed with respect to parameters that contribute to a better understanding of the rock's response to tunnelling. A study has been initiated with the goal of investigating seismic background noise, identifying suitable equipment and optimising the placement of the monitoring stations with respect to the geometric configuration of the repository, geoscientific conditions on the site and conceivable sources of disturbance. If the study shows that it is warranted to install a local seismic network, it should be in operation before the tunnel works begin.

7.3.9 Drilling

Straightness requirements

Drilling technology that meets the needs of detailed characterisation is judged to be available for the most part. Limited studies and development work will be carried out to optimise the technology, however. For example, SKB's high requirements on the straightness of the pilot boreholes necessitate such a study. A first step will be to conduct a thorough review of existing methods for guidance of boreholes as a basis for possible method development.

MWD measurements

A number of drilling-related parameters will be recorded while drilling is being done, a process called MWD (*Measurement While Drilling*). An ongoing project is investigating whether the programs that exist for analysis of MWD data can provide better predictions of the rock properties than has been possible so far. Recent developments on the hardware side are also being studied in the project.

7.3.10 Geodesy

Conventional systems – data transfer

The conventional geodetic systems available on the market today are judged to be satisfactory for most geodetic determinations that will be required by the construction of the final repository. However, development work is needed to adapt data transfer and data storage to the database system that SKB will develop, see Section 7.4, so that the requirements on quality, traceability and availability are met.

Geometric documentation of deposition holes

An activity that may require some method development is coordinate measurement by means of a total station or laser scanning to check geometric specifications for deposition holes (volume, diameter, straightness, etc), see Appendix 1 and Appendix 3, Section A3.13. Existing technology is deemed to be satisfactory for corresponding documentation of tunnels, however.

Measurement of borehole deviation

Existing methods for measurement of borehole deviation are still associated with considerable uncertainties, and further technical development is foreseen to address this.

7.4 Further development of tools for data handling and data storage

It is important to clarify at an early stage the requirements made by detailed characterisation on data handling. The integration between investigations, modelling, design, detailed planning and construction within the framework of the Observational Method makes high demands on efficient and traceable handling of data. The system must be able to link and present investigation results from boreholes and tunnels, including borehole traces and tunnel contours. Geometries and properties of deterministically modelled structures and rock types as well as hydrogeological and hydrogeochemical data together with tunnel layouts and contours of blasted tunnels must be able to be presented for e.g. verification that the design premises are met. The system must also be able to be used for presentation of data, both in day-to-day operation and for long-term planning.

In order to achieve this, the work processes of detailed characterisation must firstly be defined and described. Database structures and visualisation systems can then be built up on this basis. Secondly, it is essential to identify critical handover times for data to meet the needs of modelling. Development of all systems must be completed well in time before the start of construction, so that tests of individual system parts as well as integrated tests can be performed to verify system integration.

A couple of the development needs currently judged to be most urgent are:

- **Functionality of the database for handling large quantities of data.** Considerable quantities of information have to be stored, checked and approved for use and then retrieved for modelling and as a basis for predictions on a daily basis. To start with, an overhaul will be made of the existing database with regard to its general performance and data availability in relation to established requirements. The need for one or more databases with different capacity and functionality will then be explored and a development plan prepared.
- **Systems for deterministic geological modelling.** SKB's own-developed system RVS (*Rock Visualisation System*), based on the commercial CAD program MicroStation, was used during the site investigations. The need for continuous geological modelling, aimed at generating predictions and providing a basis for construction-related decisions, imposes high demands on robustness and user-friendliness. A requirement specification will be prepared that takes into account the new work processes during construction and operation. An evaluation will be made of commercial systems (besides RVS) against this list of requirements and the need for adaptation of these systems. In-house development of systems is also a possibility.

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Unpublished documents will be submitted upon request to document@skb.se.

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Unpublished documents

SKBdoc id, version	Title	Issuer, year
1199888 ver 1.0	Verksamhet, ledning och styrning – uppförande av slutförvarsanläggningen	SKB, 2010

Appendix 1

The role of detailed characterisation in meeting the design premises

This appendix presents and describes the design premises that influence the design of the detailed characterisation programme in one way or another. The design premises consist of a number of direct or indirect requirements on the facility's underground openings and the surrounding bedrock, mainly to guarantee long-term safety. By direct requirements is meant design premises that relate to the inherent barrier function of the bedrock. By indirect requirements is meant design premises intended to ensure that the design premises for other barriers (mainly buffer and backfill) can be fulfilled. In addition to these long-term safety requirements, requirements are made on the technical function of the facility during its construction and operation.

The table below presents and describes the design premises referred to. They are grouped into the following categories:

- Design premises regarding the barrier function of the bedrock.
- Design premises regarding underground openings and bedrock in order for the design premises for other barriers to be fulfilled.
- Design premises regarding underground openings and bedrock for the facility's technical function during its construction and operating time.

The role of detailed characterisation is explained in the middle column, while the status and development need for characterisation methods are commented on in the right column.

Table A1-1. Design premises relating to the rock's barrier function.

Design premise (taken from /SKB 2009/)	Role of detailed characterisation	Status and development need for methods
The repository volumes and depth need to be selected where it is possible to find large volumes of rock fulfilling the specific requirements on deposition holes.	Detailed characterisation serves no specific purpose for this design premise other than the fundamental and general role that can be summarised as follows: The role of detailed characterisation consists in furnishing information so that the final repository can be optimally adapted to the bedrock conditions in order that long-term safety can be guaranteed. This includes continuously updating models with an increasing degree of detail and with diminishing uncertainties. It is not usually possible to verify a design premise solely by measuring a single parameter. Instead, multidisciplinary investigations and updated models on suitable scales are needed for analysis and verification that the requirements on the function of the rock for different repository parts are met. This leads to a general need to investigate the geological, rock mechanical, thermal, hydrogeological and hydrogeochemical properties, as well as the transport properties, of the rock.	The detailed characterisation methods are generally assessed to have a good status even now. However, some development needs have been identified, as described in Chapter 7.

Design premise (taken from /SKB 2009/)	Role of detailed characterisation	Status and development need for methods
With respect to potential freezing of buffer and backfill, the requirement of temperatures favouring the mechanical properties of the canister, surface erosion and inadvertent human intrusion, the depth should be considerable. Analyses in the SR-Can assessments corroborate that this is achieved by prescribing that the minimum depth to be as specified for a KBS-3 repository, i.e. at least 400 m.	This design premise has been verified based on the results of the site investigation /SKB 2008/ and the evaluation in SR-Site /SKB 2011/.	
The groundwater composition in rock volumes selected for deposition holes should, prior to excavation, fulfil SR-Can function indicator criterion R1 on favourable chemical conditions. This function indicator criterion, which should also be seen as a design premise, states: • Reducing conditions • Salinity; TDS; limited • Ionic strength; $[M^{2+}] > 1$ mM • Concentrations of K, HS^-, Fe; limited • pH; pH < 11 • Avoid chloride corrosion; pH > 4 or $[Cl^-] < 3M$ (When quantitative criteria could not be given, the term "limited" was used to indicate favourable values of the safety function indicators).	This design premise has been verified based on the results of the site investigation /SKB 2008/ and the evaluation in SR-Site /SKB 2011/. Some follow-up verification can be done during construction and operation of the facility, but special consideration must be given to how the chemical parameters are determined by the groundwater flow pattern and the importance of obtaining representative measurement and sampling results. After blasting of deposition tunnels, undisturbed conditions will no longer prevail. Chemical testing within a deposition area regarding this design premise will therefore focus on borehole investigations before the actual rock works commence.	Supplementary and verifying hydrochemical investigations in underground boreholes focused on the deposition area will be conducted using the same basic methodology as during the site investigation phase. However, the conditions for sampling differ in that the underground facility is under hydrostatic pressure, so the samples are taken from flowing boreholes or borehole sections. It is believed that sampling, analysis and modelling can be carried out using known and available methods, but modifications will be necessary for underground application during construction and operation of the final repository so that established quality requirements are met, see also Chapter 7, Section 7.3.6.
The buffer geometry (e.g. void spaces), the buffer water content and distances between deposition holes should be selected such that the temperature in the buffer is <100°C.	Detailed characterisation should progressively update (verify and detail) the thermal models for the deposition areas of the final repository. The data comes mainly from geological mapping of boreholes and underground openings, since the dependence of the thermal properties on rock type is well known. Geophysical logging and laboratory analyses of drill cores provide complementary information. Updated models describe the spatial distribution of rock types and the related distribution of thermal conductivity. Subordinate rock types with anomalous thermal properties are hereby of particular interest. Field tests at repository depth on a scale that is relevant for the canister can be considered to verify the design premise.	It is believed that detailed characterisation of the rock related to this design premise can mainly be carried out using known and available methods. Certain development efforts will be made, e.g. to improve geophysical methods and field tests, see Section 7.3.4. Geological mapping is mainly done using established SKB methodology. However, a newly developed mapping system will be put into use, see Sections 7.3.1 and 7.3.2. Further development of a methodology for interpretation of results and thermal modelling will also be done, see Section 7.2.1.
Deposition holes are not allowed to be placed closer than 100 m to deformation zones with trace length longer than 3 km.	The role of detailed characterisation in ensuring that the design premise is fulfilled is to progressively update knowledge of these deformation zones. The issue of uncertainties concerning their geometries and other properties will be re-examined in conjunction with model updates. If necessary, targeted investigations will be initiated for the purpose of reducing the uncertainties to an acceptable level.	Besides certain adaptation of existing methods for underground use in connection with the construction and operation of the final repository, it is judged that detailed characterisation relevant to this design premise can be carried out using known and available investigation and modelling methodology.

Design premise (taken from /SKB 2009/)	Role of detailed characterisation	Status and development need for methods
Deposition holes should, as far as reasonably possible, be selected such that they do not have potential for shear larger than the canister can withstand. To achieve this, the EFPC criterion should be applied in selecting deposition hole positions. *Note 1:* *Fractures and deformation zones of such a length that they could cause such shear are referred to in this report as "large fractures". According to the EFPC criterion, a canister position should be rejected if it is intersected by a "large fracture" that can be followed around the entire tunnel perimeter. Furthermore, if a "large fracture" intersects five or more deposition holes it should be rejected.* *Note 2:* *SKB's ongoing analyses of how "large fractures" need to be constituted in order to be able to shear off a canister indicate that the EFPC criterion is conservative. A large portion of the fractures that can be followed around the entire tunnel perimeter are too short to shear a canister. The objective is to define a more realistic criterion and to develop an investigation methodology that is able to identify with sufficiently good certainty all "large fractures" that fall within such a new criterion.*	Detailed characterisation related to this design premise and the given EFPC criterion aims at mapping the walls, ceilings and floors of the deposition tunnels with sufficient accuracy to permit detection of the "large fractures" that can be followed around the entire tunnel perimeter. Furthermore, "large fractures" that intersect five or more deposition holes will be identified by investigations from the tunnel or in pilot holes, whereby progressive modelling is an essential element. Besides direct geological investigations, geophysical methods (radar and seismic) and hydraulic tests will be employed. Detailed characterisation using the aforementioned methods will evaluate step-by-step whether the design premise is fulfilled and whether the deposition position can be regarded in this respect as acceptable for deposition. The purpose of this stepwise characterisation is to avoid drilling of deposition holes in positions that will not be accepted. The methodology is illustrated in Figure 4-8. If a new, more realistic criterion for "large fractures" is determined in accordance with Note 2, there will probably be greater demands on determining the properties of the "large fractures" in order to assess their propensity to move. The principles illustrated in the figure are also judged to apply if the criterion is changed.	The existing method for tunnel mapping is adequate for detection of "large fractures" in the tunnel wall. Further development based on the aforementioned radar and seismic methods is required for early identification and characterisation of "large fractures" that intersect five or more deposition holes, but also of methodology that utilises different types of hydraulic methods. This applies to an even higher degree if a more realistic criterion for "large fractures" is developed. The development work will initially consist of identifying which fracture properties can be detected by a given investigation method. The application of the methods in the different steps will further be studied for the purpose of arriving at an expedient method package. These studies are being conducted in part in cooperation with Posiva. A methodology for final mapping of fractures in deposition holes has not been established, but is considered possible to develop without any great difficulty.
The total volume of water flowing into a deposition hole, for the time between when the buffer is exposed to inflowing water and saturation, should be limited to ensure that no more than 100 kg of the initially deposited buffer material is lost due to piping/erosion. This implies, according to the present knowledge, that this total volume of water flowing into an accepted deposition hole must be less than 150 m^3.	The Design and Construction Report /SKB 2010/ states that the design premise is deemed to be fulfilled if the inflow to the deposition hole is less than about 0.1 l/min. This is a measurable quantity, and fulfilment of the design premise can thus be assessed by measurement. A first measurement can be made in the pilot holes, permitting a preliminary assessment of fulfilment of the design requirement. Final verification can be made just before the bentonite and canister are to be emplaced in the deposition hole.	It is judged that inflow measurement, regardless of whether it is done manually or by recording instruments, will be able to be carried out using known and available methods and therefore requires no special development initiatives, aside from modification of measurement instruments for the task at hand.
Fractures intersecting the deposition holes should have sufficiently low connected transmissivity (a specific value cannot be given at this point). *Note 1:* *The design premise is judged to be fulfilled if the condition regarding inflow to deposition holes is fulfilled.* *Note 2:* *The design premise will probably be complemented by a specified maximum value.*	No special initiative beyond the above is planned for the time being. In order to address Note 2, some type of hydraulic testing is planned in addition to inflow measurement in pilot holes as described above.	In order to address Note 1: Hydraulic tests, including interference tests between pilot holes in deposition holes, can be carried out using known technology. The methodology for evaluation and modelling to verify fulfilment of the design premise will be developed as a part of the integrated modelling methodology on the tunnel scale.

Design premise (taken from /SKB 2009/)	Role of detailed characterisation	Status and development need for methods
Before canister emplacement, the connected effective transmissivity, integrated along the full length of the deposition hole wall and as averaged around the hole, must be less than 10^{-10} m^2/s. *Note 1:* *The Rock Line Report describes that elevated transmissivity outside the borehole wall can result from hole drilling due to a mechanically formed excavation-damaged zone or due to stress redistribution.*	It is not judged possible to carry out direct measurement of flow along the deposition hole wall routinely. Verification that the design premise is fulfilled will instead be based on the development of a reference method for drilling of the deposition holes that is verified to fulfil this design premise. The rock stress situation will be further investigated with a focus on repository depth, which means that the orientation of the deposition tunnels can be established with greater certainty. It is foreseen that some form of indirect verification of the design premise by means of follow-up measurements of the mechanical properties of the hole wall will be carried out during preparation of the deposition holes. High-frequency seismic or radar technology can be used for this, but a measurement programme has not yet been defined.	A methodology for the follow-up measurements of the properties of the hole wall remains to be developed. Development of methods is being pursued in part in cooperation Posiva. See also Sections 7.3.2, 7.3.3 and 7.3.5.
Excavation induced damage should be limited and not result in a connected effective transmissivity, along a significant part (i.e. at least 20–30 m) of the deposition tunnel and averaged across the tunnel floor, higher than 10^{-8} m^2/s. Due to the preliminary nature of this criterion, its adequacy needs to be verified in SR-Site. *Note 1:* *The Rock Line Report describes that the formation of an excavation-damaged zone around the tunnel is affected not only by the drill-and-blast method, but also by the orientation of the rock stresses in relation to the tunnel.*	It is not judged to be either practically possible or necessary to continuously verify the hydraulic design premise by means of measurements. Verification of its fulfilment will instead be based on the development of a reference method for rock excavation that is verified to fulfil this design premise. The rock stress situation will be further investigated with a focus on repository depth, which means that the orientation of the deposition tunnels can be established with greater certainty. It is foreseen that some form of indirect verification of the design premise by means of follow-up measurements of the mechanical properties of the tunnel wall that can cause elevated transmissivity will also be carried out. Measurement using high-frequency seismic and/or radar technology can be carried out for this purpose, for example. Such verification can be done continuously along the tunnel or on randomly selected tunnel sections.	Methodology for the follow-up measurements of the properties of the tunnel wall remains to be developed. Development of methods is being pursued in part in cooperation Posiva. See also Sections 7.3.1 and 7.3.3.
Below the location of the top sealing, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value needs not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones. There is no restriction on the hydraulic conductivity in the central area.	Same methods as above.	

Table A1-2. Design premises regarding underground openings and bedrock in order for the design premises for other barriers to be fulfilled (the Design and Construction Report /SKB 2010/).

Design premise (taken from /SKB 2010/)	Role of detailed characterisation	Status and development need for methods
Requirements on deposition holes in terms of volume, diameter, straightness, etc in order for the buffer to fulfil its given barrier function. The design premise comes from the buffer line and is specified with values.	Fulfilment of geometric specifications is verified by coordinate measurement using a suitable method, which is selected based on requirements on accuracy and functionality. Measurement principles may be based on total station or laser. In both cases, instrument setup is foreseen to be a key aspect. Besides use of an unsuitable methodology for drilling of deposition holes, breakout (spalling) can be caused by high rock stresses in combination with an unsuitable orientation of the deposition tunnels in relation to the principal stress directions. Rock stress measurements are therefore important for establishing an optimal orientation of the deposition tunnels, see Section 4.5.2.	Regarding coordinate measurement methods, it is foreseen that development will be needed to meet requirements on both accuracy and efficiency in execution. Both conventional and newly developed borehole methods are planned to be used for rock stress measurements, in combination with convergence measurements, see further Section 7.3.3.
Requirements on deposition tunnels in terms of volume, cross-sectional areas and breakout in order for the backfill to fulfil its given function. The design premise comes from the backfilling line and is specified with values.	Fulfilment of geometric specifications is verified by coordinate measurement using a suitable method, which is selected based on requirements on accuracy and functionality. Measurement principles may be based on total station or laser. In both cases, instrument setup is foreseen to be a key aspect.	It is judged that coordinate measurement can be done using existing geodetic methods. The selected method will be optimised for efficient application.
Requirements on deposition tunnels in terms of maximum total inflow and maximum point inflow in order for the backfill to fulfil its given function. The design premise comes from the backfilling line and is specified with values.	One role for detailed characterisation is, based on investigations in pilot holes and probe holes, to make predictions of water inflows so that effective pre-grouting can be done. After completion of the deposition tunnel it will be possible to measure the inflow to the whole tunnel. Measurement weirs are planned to be built that collect the sectional water inflow so that it can be measured by a recording flowmeter (or by manual readings). The weirs will be built according to a reference design, where a tight seal is achieved in the tunnel floor and the excavation-damaged zone. Point inflows can be measured in campaigns.	Measurement of inflows to the entire deposition tunnel does not pose any particular difficulty. Good experience is available from the Äspö HRL. This assumes that weirs providing a tight seal can be built, for which a reference design needs to be developed. A suitable method needs to be developed for measurement of point inflows, but this is not expected to pose any particular difficulty either.
The rock at the plugs in the deposition tunnels must be strong enough to bear the load of the plug without fracturing.	Rock mechanical models will provide a basis for strength calculations. Rock samples will be taken for laboratory analyses to provide input data to the model.	Existing measurement and modelling methods are adequate.
Requirements on underground openings (aside from deposition tunnels) below the top seal in the form of volume and contour so that the backfill can fulfil its given function. The design premise has not yet been specified with values.	Methods for coordinate measurement are the same as for coordinate measurement of deposition tunnels.	

Table A1-3. Design premises regarding underground openings and bedrock for the facility's technical function during its construction and operating time (the Design and Construction Report /SKB 2010/).

Design premise (taken from /SKB 2010/)	Role of detailed characterisation	Status and development need for methods
Requirements on maximum water inflows to the parts of the facility that are not deposition tunnels. The design premise is specified with preliminary values.	The inflow to tunnels and shafts will be measured in packered-off sections with recording flowmeters. This requires the construction of weirs.	The same methods will be used as for the deposition tunnels, so this point does not impose any additional requirements on the measurement methodology.

A1.1 References

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Appendix 2

Modelling methodology

An account is provided below under discipline-specific headings of the current status and new modelling premises resulting from expected new primary data from detailed characterisation. In addition, essential modelling tasks are described.

A2.1 Geology

The methodology for modelling of rock domains and deterministic deformation zones described by /Munier et al. 2003/ was applied during the site descriptive modelling phase, although slightly modified for conditions at Forsmark. The results are presented in /Stephens et al. 2007/ and /Stephens et al. 2008/. Previous methodology for geological DFN modelling has also been updated, see /Munier 2004/.

Detailed characterisation is expected to provide an improved dataset for:

- Description of steeply dipping fracture sets with the aid of information gathered under ground (ramp, shafts, tunnels with different directions and boreholes with varying orientation).
- Increased understanding of the importance of observation scale and the link between fracture data/parameters from (pilot) boreholes and exposed surfaces in tunnels.
- Description of the size of geological structures via the large exposed rock areas in tunnels, shafts and rock caverns.
- Virtually deterministic descriptions of geological structures and rock type distribution on the tunnel scale (especially in deposition areas).
- Conditioning/verification of geometric models of "large fractures" and brittle deformation zones, in part based on hydraulic connectivity observed from pressure responses and flow variations.

During construction and operation, and especially during the preparation of deposition areas, it is essential to:

- Ensure the size of the deposition area by verification of layout-determining deformation zones at repository depth.
- On the tunnel scale, continuously follow up the occurrence of amphibolite and other quartz-poor intrusive rock types, which are characterised by reduced thermal conductivity compared with the principal rock types of the site.
- Describe and, if possible, deterministically confirm minor deformation zones and "large fractures".
- Improve the description in DFN models by means of new information mainly from shafts and tunnels as well as cored boreholes drilled under ground.

For a discussion of new methods for tunnel mapping and development of new methodology for single-tunnel interpretation, see Appendix 3 and Section 7.3.1.

A2.2 Thermal properties

The geometric basis for modelling of the temperature distribution in the rock volume is the rock type distribution and the subdivision into rock domains. The methodology used for thermal modelling is based on a stochastic simulation of lithological conditions and thermal conductivity applied to individual rock domains /Back and Sundberg 2007/. A thermal description of Forsmark is presented by /Back et al. 2007/ and /Sundberg et al. 2008/. Detailed characterisation is expected to provide an improved dataset for:

- Follow-up of *Thermal Rock Classes*, TRCs, defined from surface boreholes based on rock type mapping of cores from pilot boreholes and of tunnels. This is expected to be able to be carried out efficiently and continuously and permits a virtually deterministic description of thermal conductivity.
- Supplementary determinations of thermal properties in the laboratory.
- Verifying tests of thermal conductivity at a scale of 1–10 metres.

With this in mind, the modelling strategy for thermal modelling during construction and operation needs to be reconsidered.

A2.3 Rock mechanics

The strategy for modelling of the rock's deformation and strength properties (for intact rock, fractures and fractured rock mass) as well as modelling/description of rock stresses during the site investigation phase is presented by /Andersson J et al. 2002a/. The resulting rock mechanics modelling of Forsmark is described by /Glamheden et al. 2008/. Detailed characterisation is expected to provide an improved dataset for:

- Description of the magnitude of the maximum principal stresses as well as precise determinations of the orientations of the horizontal principal stresses based on results from, above all, convergence measurements and renewed borehole measurements (under ground).
- Analysis of the stress situation (geometry and magnitudes) in relation to the location and extent of deformation zones based on updated models of deformation zones in the deposition area.

A2.4 Hydrogeology

Methodology for site descriptive hydrogeological modelling is presented in /SKBdoc 1238536/. /Follin 2008/ and /Follin et al. 2008/ present the hydrogeological model of Forsmark.

Detailed characterisation is expected to provide an improved dataset for:

- Attribution of properties to flowing structures observed in shafts and tunnels (where effects of scale, two-phase flow and skin are also taken into consideration).
- Determination of size of fractures (see Section A2.1, *Geology*).
- Determination of the hydraulic extent of structures (connectivity) over large distances (of importance primarily in deposition areas).
- Reduction of uncertainties and thereby increased confidence in the hydrogeological description.

Essential tasks for hydrogeological modelling during construction and operation, and especially during the preparation of deposition areas, include to:

- Carry out virtually deterministic hydraulic characterisation of local minor brittle deformation zones and "large fractures" identified as a part of the geological description of the rock around the deposition tunnels.
- Determine potential positions of deposition holes associated with low groundwater flows.
- By analysis of data from direct hydraulic tests, but also from other types of disturbances (planned and unplanned), create increased understanding for the geometry and connectivity of conductive structures over long distances.

Monitoring above and below ground of hydrogeochemical changes, together with temperature logging in boreholes, can also be utilised to indicate/verify hydraulic connectivity, see experience from Äspö HRL /Andersson P et al. 2002b, Rhén and Smellie 2003/. See further discussion of integration in Section 3.2.2.

A2.5 Hydrogeochemistry

The strategy for hydrogeochemical modelling /Smellie et al. 2002/ has been progressively developed during the site investigation phase. The final hydrogeochemical site description for Forsmark is presented by /Laaksoharju et al. 2008/. Detailed characterisation is expected to provide an improved dataset for:

- Quantification of buffering capacity with regard to redox and alkalinity along flow paths.
- Description of the final repository's impact on hydrogeochemical conditions based on data from time series (from boreholes both above and below ground, measurement weirs etc).
- Achieving greater process understanding and confidence in hydrogeochemical descriptions.

Essential tasks for hydrogeochemical modelling during construction and operation include:

- Explaining observed variations in the distribution and concentration of sulphide and dissolved uranium.
- Evaluation and further handling of hydrogeochemical data collected in a disturbed environment. Important experience will be obtained from ongoing site descriptive modelling at the Äspö HRL and modelling in conjunction with the extension of SFR as well as from Posiva´s ONKALO facility.

Some hydrogeochemical model updating will take place, but most of the modelling is planned to be done in conjunction with updated complete site descriptions.

A2.6 Transport properties of the rock

Guidelines for modelling of the transport properties of the rock during the site investigation phase are presented by /Berglund and Selroos 2004/, and the site descriptive transport model for Forsmark is described by /Crawford 2008/. The quantification of flow-related retention properties has been developed during the site investigations, based on both hydrogeological DFN and continuum models. This development should result in an updated strategy for transport modelling for detailed characterisation.

The users have not expressed any special needs for new types of data. Verification of fulfilment of design premises is mainly provided by results from *Hydrogeology*. The main task for transport modelling during construction and operation is to reduce uncertainties and increase confidence in the description.

During the construction phase, the work is focused on securing necessary supplementary data in relevant databases. Of particular importance is early initiation of long-term experiments in the laboratory, mainly diffusivity measurements on rock samples. Similarly, simplified variants of in situ diffusion experiments resembling LTDE /Widestrand et al. 2010/ in the Äspö HRL can be carried out if necessary to verify laboratory results, Section 7.3.7. Continuous follow-up/modelling of transport properties is not expected to be done during the construction phase, but will take place in conjunction with the updating of complete site descriptions.

A2.7 Surface systems

A strategy for modelling of surface systems (ecosystems) is described by /Löfgren and Lindborg 2003/, while a description of the surface system at Forsmark is provided by /Lindborg 2008/. As far as the surface systems are concerned, the results from the site investigation are regarded as robust and applicable to safety assessments and evaluations during the construction phase. Monitoring of relevant parameters continues, however, in order to supplement relevant time series.

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SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.
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SKBdoc id, version	Title	Issuer, year
1238536 ver 1.0	A framework for discipline consistent and 'partially validated' models within Site-descriptive modeling versions 2.2–2.3	SKB, 2006

Appendix 3

Methods and instruments

A3.1 Overview

This appendix presents an overview of investigation methods and instruments at SKB's disposal that have been employed both above and below ground. The most recent above-ground use was for the site investigations at Forsmark and Laxemar 2002–2007 and for the preliminary investigations 2007–2009 prior to the extension of SFR at Forsmark. The main underground use was in the research activities at the Äspö HRL and, to a lesser extent, the preliminary investigations at the SFR repository.

The method compilation has been done according to discipline (in one case related methods have been grouped together) as follows:

- Drilling.
- Borehole investigations connected with drilling.
- Geological and geophysical borehole investigations.
- Rock mechanical investigations.
- Thermal investigations.
- Hydrogeological borehole investigations.
- Hydrogeochemical investigations.
- Investigations concerning transport properties of the bedrock.
- Mapping of underground openings.
- Non-borehole-related surface investigations.
- Monitoring.
- Geodetic investigations.

As is evident from the bulleted list, seven of the eight first points consist of drilling and investigations in boreholes. The points "rock mechanical investigations" and "monitoring" also include measurements in boreholes to a great extent. Even though borehole investigations will play an important role in the detailed characterisation programme, the list can give a slightly exaggerated impression of the importance of the borehole investigations in relation to other investigations. The driving of tunnels and shafts in and above the repository area provides a much better opportunity to study the structures in the rock in three dimensions than when only drill cores and other rock samples were available. The exposed rock surfaces, especially at repository depth, will gradually increase and eventually cover large areas. Tunnel documentation in the form of geological mapping and hydrogeological and hydrogeochemical observations will thereby be of crucial importance in providing knowledge of the rock volume in which the final repository will be built.

Under each heading, an overview is given of the relevant method in its current status. More or less extensive technology development and modification needs have been identified for certain methods and instruments; this is presented in Section 7.3. Just as the selection of methods and instruments in this appendix is preliminary, the technological development plans are still in preparation, so modifications and further details can be expected in the future.

A3.2 Drilling

Different types of borehole measurements are fundamental in geoscientific investigations that cover large volumes of soil and rock, regardless of whether the investigations are performed from the ground surface or from tunnels. The *drilling activity* in itself is an investigation method, since many observations made during drilling provide a direct indication of important properties of the penetrated volume.

Figure A3-1 illustrates drilling activities above and below ground. The two most common types of investigation drilling are based on percussion drilling and core drilling technology, and both methods have well developed systems for both surface and underground drilling. In percussion drilling, where the drilling head or hammer has both a rotary and percussive action, the rock is crushed to a finely divided material called drill cuttings. The drill cuttings are flushed to the mouth of the hole by the flushing medium, which in the case of surface drilling generally consists of compressed air. The normal flushing medium for probe drilling under ground is water.

In core drilling, the drilling head consists of an annular drill bit, on which the cutter consists of a diamond-impregnated alloy, see Figure A3-2. During drilling a cylindrical drill core is cut out and gradually fed into the core barrel, which, after three (or sometimes six) drilled metres, is lifted up to the mouth of the hole by a wireline winch (called *wireline* technology). The flushing medium is water, which is pumped down into the borehole under high pressure to cool the drill bit and bring up the cuttings. It is important for subsequent borehole investigations that cuttings removal from the hole is effective so that the borehole is kept as clean as possible. SKB has developed a method for deep cored boreholes drilled from the surface where the upper part of the borehole, generally about 50–100 m, is percussion-drilled to a large enough diameter to permit pumping equipment to be installed (the telescopic borehole method). By constant pumping during the subsequent core drilling phase, the groundwater level in the borehole can be kept lowered, facilitating the upward flow of groundwater, flushing water and drill cuttings in the borehole.

When drilling takes place from a tunnel below the groundwater table, the borehole will remain under hydrostatic pressure, making cuttings removal even more effective, especially if the hole is more or less horizontal or upward-directed.

Figure A3-1. *Top left: percussion drilling from the ground surface with simultaneous sampling of drill cuttings; top right: core drilling from the ground surface. Bottom left: percussion drilling (probe drilling) below ground; bottom right: core drilling below ground.*

Figure A3-2. *At left: core drill bit. At right: mapping of drill cores from a whole cored borehole mounted on a mapping table.*

In order to ensure that groundwater samples taken from the drilled hole are as representative as possible of the current groundwater situation, SKB has developed a system to prepare the flushing water for use in the borehole, see /Almén and Zellman 1991, Almén and Stenberg 2005/ as well as P-reports that present results from core drilling during the site investigations at Forsmark and Laxemar, for example /Claesson et al. 2006 and Ask et al. 2006/.

Core drilling will be the preferred drilling method for pilot boreholes and other investigation boreholes. A type of percussion drilling called top hammer drilling is used for probe drilling prior to rock excavation as well as for blast hole drilling and grout hole drilling.

Figure A3-3 illustrates a drilling, investigation and production sequence that will play an important role in construction of the final repository. It includes the following steps:

1. Pilot drilling with borehole investigations during and after drilling for assessment of the rock properties along a tunnel length of 200–300 m (e.g. an entire deposition tunnel).
2. Probe drilling with borehole investigations during and after drilling for assessment of the rock properties for the next 4–5 blasting rounds.
3. Blast hole drilling (with subsequent blasting round and rock excavation).
4. Tunnel mapping.
5. Points 3 and 4 are repeated (four times in this example).
6. Points 2, 3 and 4 are repeated until the end of the pilot hole is reached. Then the sequence 1–6 starts again.

Both percussion and core drilling are planned to be used in any additional surface boreholes.

A3.3 Borehole investigations connected with drilling

During and immediately after drilling (percussion drilling or core drilling), *different types of measurements, recordings and samplings are carried out*. The most important are described in the infobox on the next page. Different steps in some of these methods are also illustrated in Figure A3-4. Some of the activities are also commented on in later sections in this appendix.

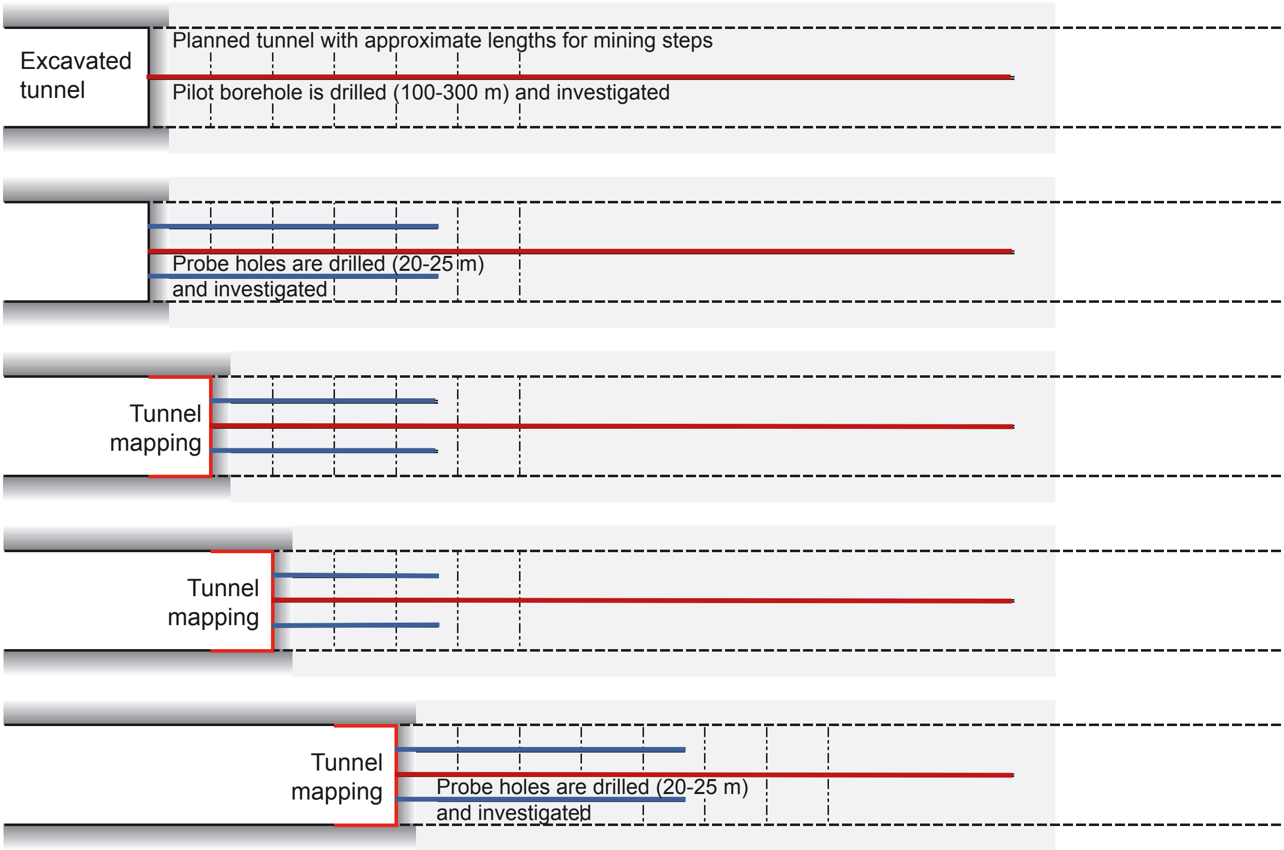

Figure A3-3. *Illustration of and schematic locations for the recurrent steps pilot drilling and probe drilling with borehole investigations and tunnel mapping during routine driving of a tunnel.*

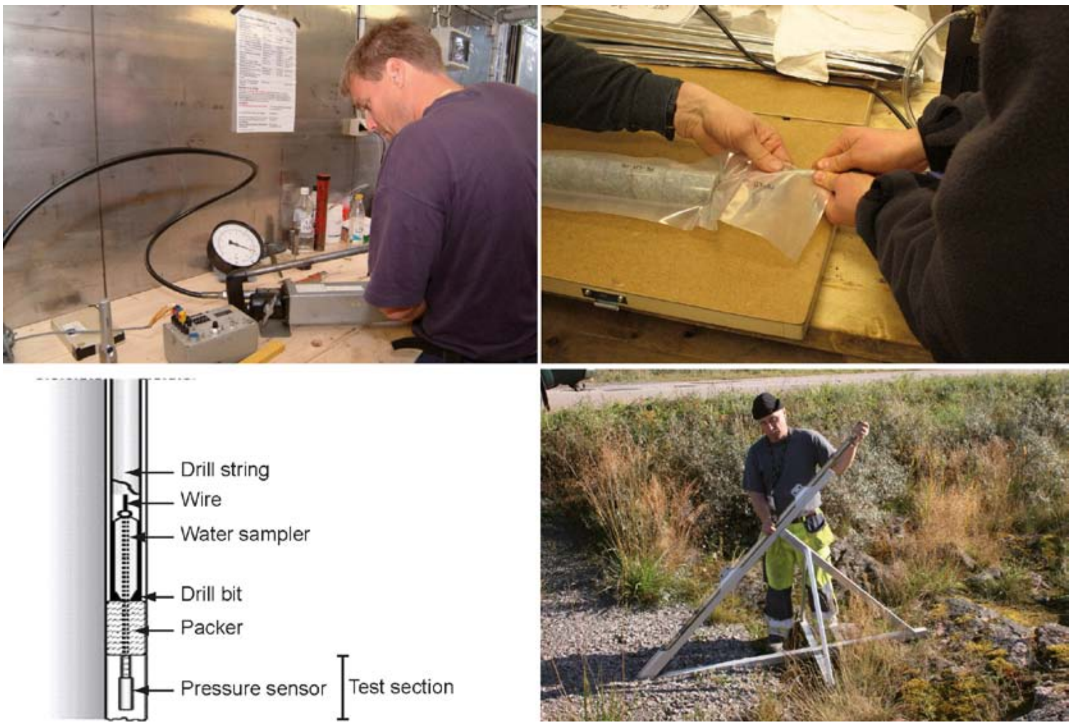

Figure A3-4. *Top left: biaxial testing of an overcoring (hollow) drill core in connection with rock stress measurement; top right: packing of sawn-out drill core sample for shipment to laboratory. Bottom left: schematic drawing of wireline probe for hydraulic testing/water sampling during drilling; bottom right: Flexit Smart Tool probe intended for measurement of borehole deviation.*

A3.4 Geological and geophysical borehole investigations

Borehole geophysics supports geological characterisation, so geological and geophysical methods are dealt with together in this section. A standardized programme for investigations of percussion-drilled and cored boreholes was carried out during the site investigations at Forsmark and Oskarshamn. It included *borehole TV logging (BIPS), borehole radar and a number of conventional geophysical logging methods (electrical, magnetic, radiometric and acoustical methods as well as caliper, temperature and electrical conductivity of the borehole fluid).* Similar borehole investigations have been carried out within the Äspö HRL's research programme. Photos illustrating the field work are shown in Figure A3-5.

Infobox.

Measurements, recordings and samplings during and immediately after drilling

- During core drilling, rock samples are taken in the form of a **cylindrical drill core**, usually in three-metre lengths, in principle continuously along the entire borehole (some core losses may occur for technical reasons, however). This is the most important type of sampling from a geological point of view which, via the results of core mapping (Figure A3-2, see also Section A3.4 about Boremap mapping), possibly in combination with the results of ground mapping of rock outcrops, lays the foundation for geological modelling in those situations when information from tunnels and underground openings is not available. Characterisation of drill cores will also be of great importance as a prediction tool during construction of the final repository, since pilot drilling with core extraction will be carried out regularly before a new tunnel is mined. After tunnelling, the results of Boremap mapping of the pilot hole core will be cross-checked against the results of tunnel mapping. Immediately after drilling, or later, **large or small samples of rock matrix and/or fracture-filling mineral can be sawn out** of the drill cores for various kinds of **laboratory analyses**, see Figure A3-4.
- During percussion drilling from the ground surface or a tunnel, **drill cutting samples** can be taken out at the desired frequency for visual rock type assessment or mineralogical analysis (see Figure A3-1).
- **MWD (*Measurement While Drilling*)** consists of measurements and samplings carried out during drilling of parameters that are of direct geoscientific interest and parameters that are primarily of drilling-related importance. The former include flushing water flow and pressure, salinity and oxygen concentration of the flushing water, as well as concentration of added tracer, which is analyzed in test series of flushing and return water. Drilling-related parameters include e.g. penetration rate, feed force, rotation pressure and rotation speed. Some measurements and samplings can be carried out manually, but recording instruments are generally used. Modern drilling rigs are often equipped with computerised control systems that automatically record drilling-related parameters for optimal efficiency. Some of these parameters are also of geoscientific interest. Other, geoscientifically important parameters, mainly ones related to the flushing and return water, are recorded by other measurement instruments and stored temporarily in another field computer. After concluded drilling, the MWD data that are of geoscientific interest are stored in SKB's database for later analysis.

  MWD measurements may also include **hydraulic tests during drilling**. They can be performed by means of several different methods. In percussion drilling from the surface, the outflow from the borehole (caused by the pumping effect created by the air pressure) is measured at set intervals. In underground percussion and core drilling, the outflow can be measured at an arbitrary drilling length. In core drilling from the ground surface, tests are often performed with a specially made wireline probe, which permits pumping tests, groundwater pressure measurements and water sampling, see Figure A3-4 and drilling reports from the site investigations, e.g. /Ask et al. 2006/. This method can also be adapted to underground conditions.
- By **hydraulic observations in surrounding existing observation holes during drilling** is mainly meant recording of groundwater head (measured as pressure) in observation boreholes sectioned by packers during drilling of a new borehole. The observation boreholes may be situated at greater or lesser distances from the hole being drilled. The sectioning of the boreholes may be either simple, e.g. a borehole closure with pressure sensor at the borehole mouth, or more advanced involving installation of a multiple packer system. The recordings can be used on a larger scale to identify hydraulic isolation (barrier action), or alternatively hydraulic connectivity between different parts of the repository. On a more limited scale, e.g. tunnel scale, this type of information can be used for interpretation of the absolute geometry of a conductive structure such as a "large fracture", another larger deformation zone, etc.
- Several methods exist for rock stress measurements, see Section A3.5. One of them involves **overcoring measurements**, see Figures A3-4 and A3-9, as well as /Almén and Stenberg 2005/.
- After concluded drilling, a special tool is used to **mill centimetre-deep grooves** at regular intervals in the borehole wall to permit **length calibration** of the borehole logging methods that will later be used in the borehole (see drill reports from the site investigations, e.g. /Claesson et al. 2006/).
- It is technically impossible to drill long boreholes completely straight. So-called **deviation measurement** of the borehole is therefore carried out after drilling for the purpose of determining the position of the borehole in space (x, y and z coordinates), usually at three-metre intervals all the way from the mouth to the bottom of the borehole. The deviation measurements are generally done using both an optical method and a magnetometer-accelerometer method. During the site investigations, SKB further developed the methodology for deviation measurements, whereby a method was also developed for quantification of uncertainties in deviation data, see /Munier and Stigsson 2007/.

Figure A3-5. *Geophysical borehole investigations. From left: 1) BIPS logging in underground hole, 2) conventional geophysical borehole logging in surface borehole and 3) interior from measurement bus for geophysical logging.*

Conventional systems for geophysical logging are described in e.g. /Almén and Stenberg 2005/. Of other methods, *borehole-TV logging* with the *BIP system*, *(Borehole Image Processing System)*, and *borehole radar*, the RAMAC system, have been used frequently by SKB ever since the 1980s, whereas *acoustic televiewer* was routinely applied by SKB for the first time during the site investigations. The digital BIP system uses a video camera aimed downward/forward in the borehole, which generates a continuous annular colour image of the borehole wall. Within the image, a ring consisting of 360 pixels indicates what data are recorded digitally by the system. As the camera moves downward/forward in the borehole, the borehole wall is passed over by the pixel ring and scanned 50 times per second. The video images can be studied at three different resolutions (1, 0.5 and 0.25 mm), corresponding to three logging rates (1.5, 0.75 and 0.38 m/min, respectively). An example of a BIPS image is shown in Figure A3-6. SKB's version of the BIP system is modified for use of the same battery and fibre-optic cable system used in the RAMAC system. For a more detailed description of the BIP system, see e.g. /Almén and Stenberg 2005/.

The RAMAC system and the underlying theory are described in detail in /Falk et al. 1989/ and Sandberg et al. 1991/. The system consists of a transmitter, a receiver, a signal control unit, a data collection system and a display unit. The functional principle in single-hole measurement is as follows:

In borehole radar, the dipole-type transmitter antenna generates a high-frequency (20–250 MHz) electronic pulse (radar wave) that propagates through the rock until it reaches a structure with anomalous electrical properties, such as a deformation zone or a lithological boundary, where the

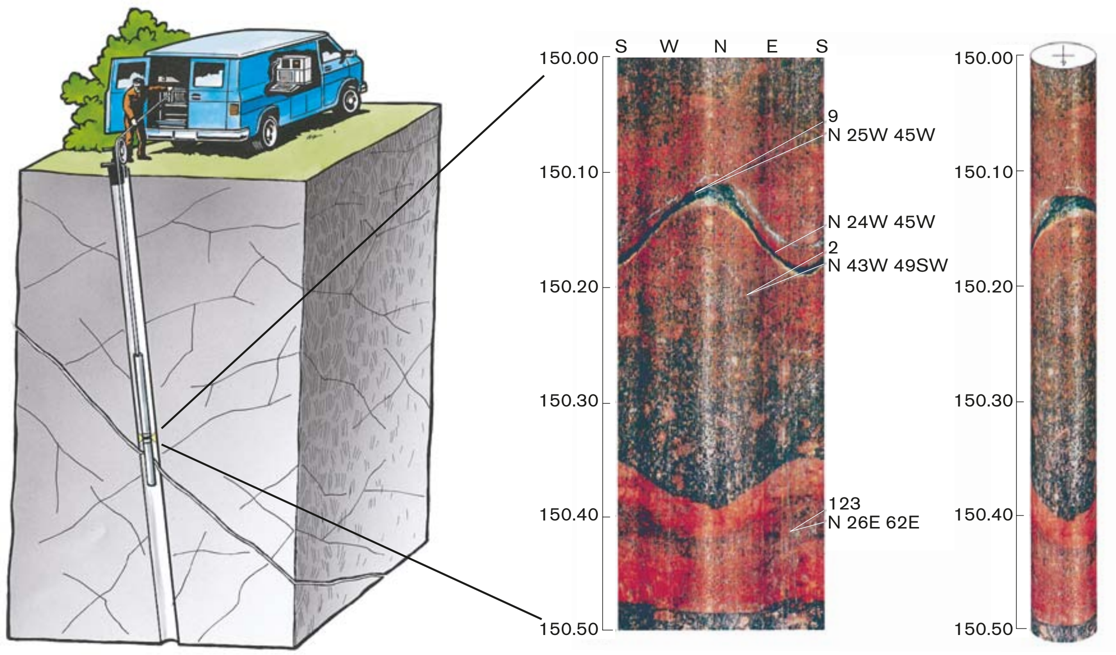

Figure A3-6. *At left: Illustration of BIPS logging; middle: unfolded BIPS image of borehole wall; at right: BIPS image rolled up like a drill core.*

radar wave is reflected back to the receiver antenna, amplified and recorded as a function of the time. Measurements can be performed at 0.5 m intervals in the borehole, and the results are displayed in the form of a radar diagram, see Figure A3-7. With a dipole antenna it is only possible to determine the orientation of structures in relation to the borehole axis. If a directional antenna is used, consisting of an array of four separate receiver loops, the structure's absolute orientation can be determined.

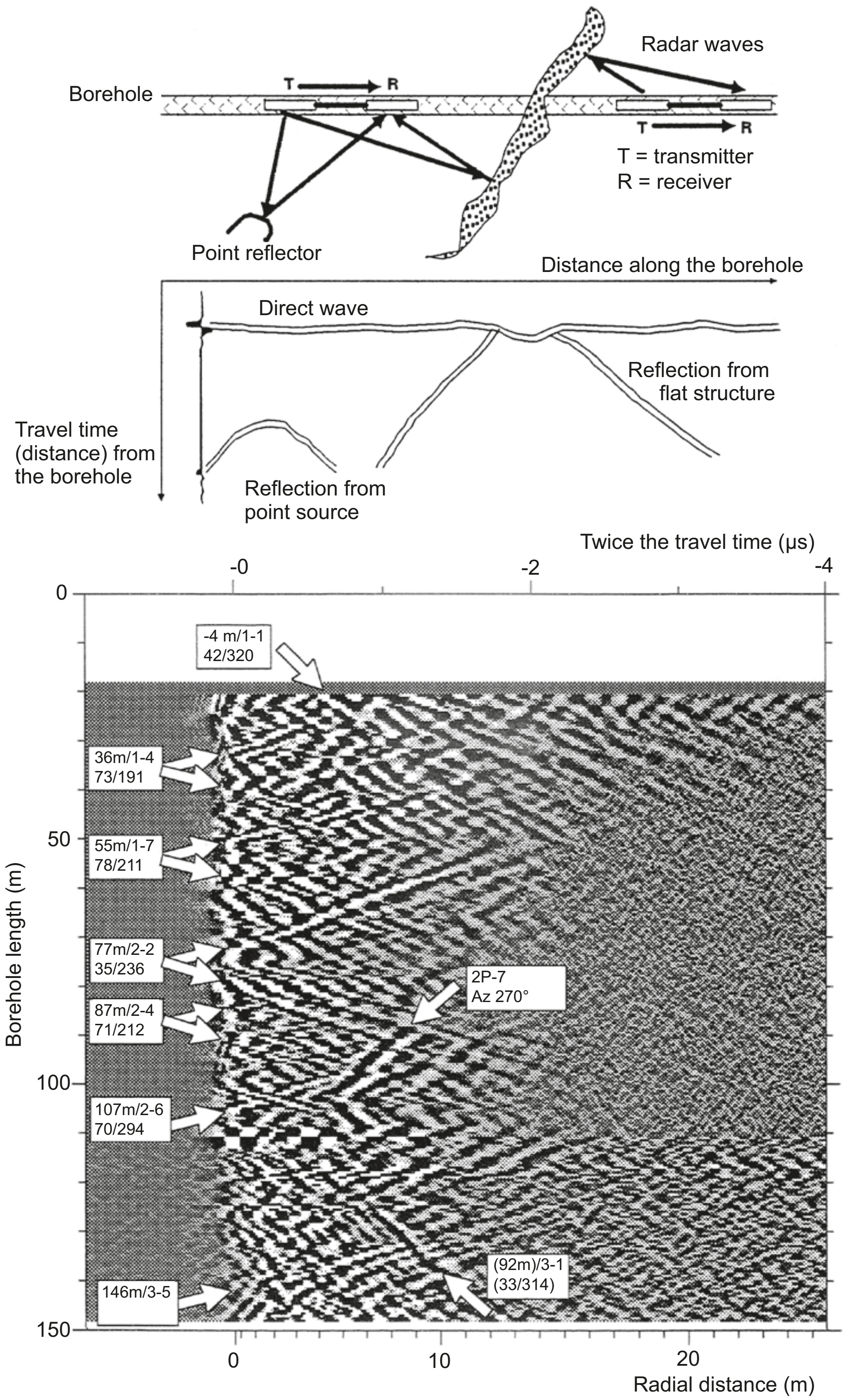

Figure A3-7. Above: Principle of borehole radar measurement. Below: An example of a radar diagram from a borehole in the Äspö HRL drilled towards a major deformation zone (zone NE-1).

The range of penetration of the radar pulse is a function of both the transmitter frequency used (the lower the frequency, the greater the range of penetration) and the properties of the bedrock. In favourable cases, above the groundwater level or if the groundwater has low salinity, the penetration range of the radar wave can be up to several tens of metres in crystalline rock. The radar wave is attenuated as the salinity of the groundwater increases, however. In measurements in the Äspö HRL, where the salinity is around 10 ‰, a normal penetration range of 20–25 m has been reached /Almén and Stenberg 2005/.

The *acoustic televiewer* is a logging instrument with multiple functions (see also Section A3.5). The instrument records an image of the borehole wall by acoustic means and can thereby offer supplementary information to that obtained with optical technology. The acoustic televiewer has the capacity to measure the borehole diameter with great accuracy, which means that the instrument can be used as a precision caliper for detailed mapping of variations in the diameter of the borehole. For caliper function it is of vital importance that the instrument be centred well in the borehole.

A logging programme similar to that employed during the site investigation, or variants thereof, can be expected to be employed in underground investigations as well. Special insertion equipment is required in horizontal or upward-directed boreholes, however. SKB recently had such equipment developed for use in the SFR project /Nilsson 2009/, see Figure A3-8. Performance tests of this prototype are being conducted in SFR and in the Äspö HRL, and if they show favourable results, the equipment may be used under ground in detailed characterisation as well.

The infobox in Section A3.3 mentions that mapping of the drill core takes place during or after a cored borehole is finished. In SKB's borehole investigations, a method is used where mapping of the drill core is combined with study of the images of the borehole wall from the aforementioned BIP System. With the aid of these images, fractures, lithological boundaries and ductile and other structures in the borehole wall can be oriented and the borehole wall can be preliminarily characterised with regard to rock type distribution, fracture frequency and fracture fillings. The characterisation is augmented by mapping of the corresponding section of the drill core. The combined mapping of the drill core and the borehole wall is termed *Boremap mapping*, a method that is also used for

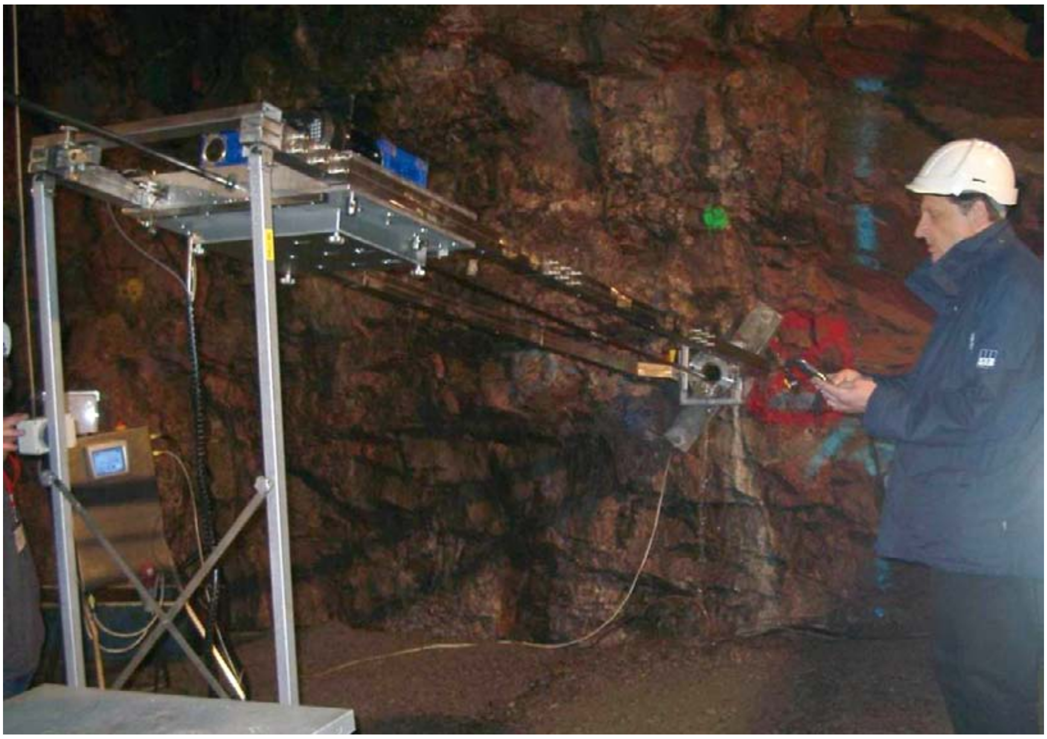

***Figure A3-8.** Insertion equipment intended for e.g. borehole geophysical equipment in horizontal, subhorizontal and upward-directed underground boreholes.*

percussion boreholes. In that case the focus is on analysis of the BIPS image, since there is no drill core, only intermittently collected drill cutting samples. In most cases it is therefore not possible to achieve as high quality in the mapping results as in Boremap mapping of cored boreholes.

The geological and geophysical investigation methods provide extensive documentation of the borehole as a basis for *single-hole interpretation*, which results in a summary assessment of the lithological and structural geology conditions in the rock penetrated by the borehole. The future planning work will have to consider whether the single-hole interpretation is to be extended to include hydraulic parameters as well, which has not been the case during the site investigations.

A3.5 Rock mechanical investigations

Rock mechanical investigation methods can be divided into several groups, primarily: 1) methods for in situ rock stress determination, 2) laboratory methods for determination of mechanical properties of the rock matrix, 3) laboratory methods for determination of mechanical and hydromechanical properties of fractures, and 4) methods for determination of mechanical properties of the rock mass.

The properties of the stress field at Forsmark are associated with some uncertainties, see /SKB 2008/. Present-day knowledge of the stress field is mainly based on **rock stress measurements** using *hydraulic methods* and *overcoring measurements* (see Figure A3-9). The most common types of hydraulic measurements are *Hydraulic Fracturing* (HF measurements) and HTPF tests*(Hydraulic Tests on Pre-existing Fractures)*. In hydraulic fracturing, so much pressure is applied in a borehole section sealed off by packers that an axial fracture is created in the borehole wall. By analysis of the pressure-time curve from the fracturing sequence, it is theoretically possible to determine the magnitude of the minimum principal stress. By making an impression of the induced fracture, it is also possible to determine the orientation of the minimum principal stress. A more modern, more efficient and more exact method of doing this orientation determination is to use borehole geophysics methodology (resistivity instrument, acoustic or optical televiewer, or a combination of these methods).

Since the HF method is two-dimensional, and thus does not characterise the entire stress tensor, it is usually combined with HTPF tests on existing fractures. The method is based on stimulation (*re-opening*) of existing open fractures. If sufficiently many fracture groups of different orientation can be located, it is possible to determine the entire stress field in terms of both magnitudes and orientations.

Figure A3-9. *Rock stress measurements at Forsmark. At left: lowering of borehole equipment for hydraulic fracturing; at right: study of freed drill core from overcoring measurement.*

In *overcoring measurements* (see Figure A3-9 and /Almén and Stenberg 2005/), drilling of a cored borehole is interrupted at the depth where overcoring measurement is planned. The normal drill bit is replaced with a much smaller coring drill bit. This is used to drill a small-diameter pilot hole in the bottom of the ordinary cored borehole. A measurement cell is placed in the pilot hole. Then the pilot borehole is "overcored" to the diameter of the original borehole, whereby a hollow cylindrical drill core is obtained. The stress relief that occurs in the freed core is recorded by strain gauges, and the data are stored in the measurement cell, which is then lifted out of the borehole together with the overcored core. Finally, the elastic properties of the hollow core are determined (Figure A3-4). In the case of successful measurements, the entire stress tensor is determined, i.e. the method is three-dimensional.

Borehole measurements using hydraulic methods and overcoring will be less resource-consuming to do during the construction phase than during the site investigations, since they will be able to be done in short holes drilled in different directions from the tunnels. The secondary stress field that arises around the tunnels is, however, a complicating factor in the evaluation of underground measurements.

SKB is currently studying two types of overcoring methods developed by Posiva in ONKALO, the *LSG and LVDT methods*. These methods are based on the same fundamental principles as conventional overcoring. But there are a number of technical and scale-related differences. LSG stands for *Long Strain Gauges* and refers to equipment with strain gauges that are approximately five centimetres long, i.e. about five times longer than the strain gauges in conventional overcoring equipment. The LSG gauges are primarily designed for application directly on as smooth a tunnel or shaft wall as possible (i.e. a tunnel or a shaft with nearly ideal geometry), e.g. a TBM tunnel or a full-face-drilled shaft. Subsequent overcoring is done with a large diameter, e.g. 127 mm. One advantage of the LSG method over conventional overcoring in narrower boreholes is that the result obtained from the LSG method represents a slightly larger measurement scale and is therefore less sensitive to small-scale heterogeneities such as grain size variations in the rock mass.

The LVDT method (*Linear Variable Differential Transformer*) is based on four pairs of LVDT transformers that are installed close to the tunnel contour in a large-diameter borehole, e.g. with a diameter of 127 mm, and that record the diametral deformations that occur during overcoring with a diameter of e.g. 200 mm. By carrying out measurements in different positions in a shaft or tunnel section of known geometry, it is possible to determine the in situ stress state by means of inverse modelling on the tunnel scale. Like the conventional overcoring method and the LSG method, the LVDT method assumes elastic conditions. The LVDT method determines, like the LSG-method, the stress state on a larger scale than the traditional overcoring method. In applying these methods in blasted tunnels and shafts, it is important that the measurements be done at a sufficiently great distance from the tunnel perimeter in order to avoid the influence of the excavation-damaged zone.

Certain information on the stress field can also be obtained from other methods, such as study of drill cores for the occurrence of *core disking* (spontaneous, time-dependent, stress-induced cracking of a part of the drill core into millimetre- or centimetre-thick disks), which provides an indication of stress concentrations in relation to the strength of the rock, and study of the borehole wall. The latter can be done by means of optical or acoustic methods. The occurrence of *borehole breakouts* and other types of stress-induced spalling of the borehole wall was studied in several cored boreholes during the site investigations (see Figure A3-10) by means of *acoustic televiewer*. The method can provide a more continuous picture at depth of orientation variations in the stress field than the point-by-point information obtained from overcoring measurements and hydraulic tests /Ask and Ask 2007/. If the method is to be used for magnitude determinations, the occurrence of continuous, full-scale stress-induced breakouts is necessary. Such breakouts have, however, not been identified in any of the investigated boreholes at Forsmark, where only sporadically occurring large breakouts have been observed. However, stress- and temperature-induced micro-breakouts are common. The televiewer's capacity to measure the borehole diameter with great accuracy permits detection of even these very small breakouts (down to the size of a mineral grain) from the borehole wall.

During detailed characterisation, *convergence measurements* will be introduced as a complement to borehole methods for continued rock stress measurements. In this method, studs are drilled into the wall at strategic places in shafts and tunnels, after which changes in their positions due to stress redistribution are measured very accurately with laser technology.

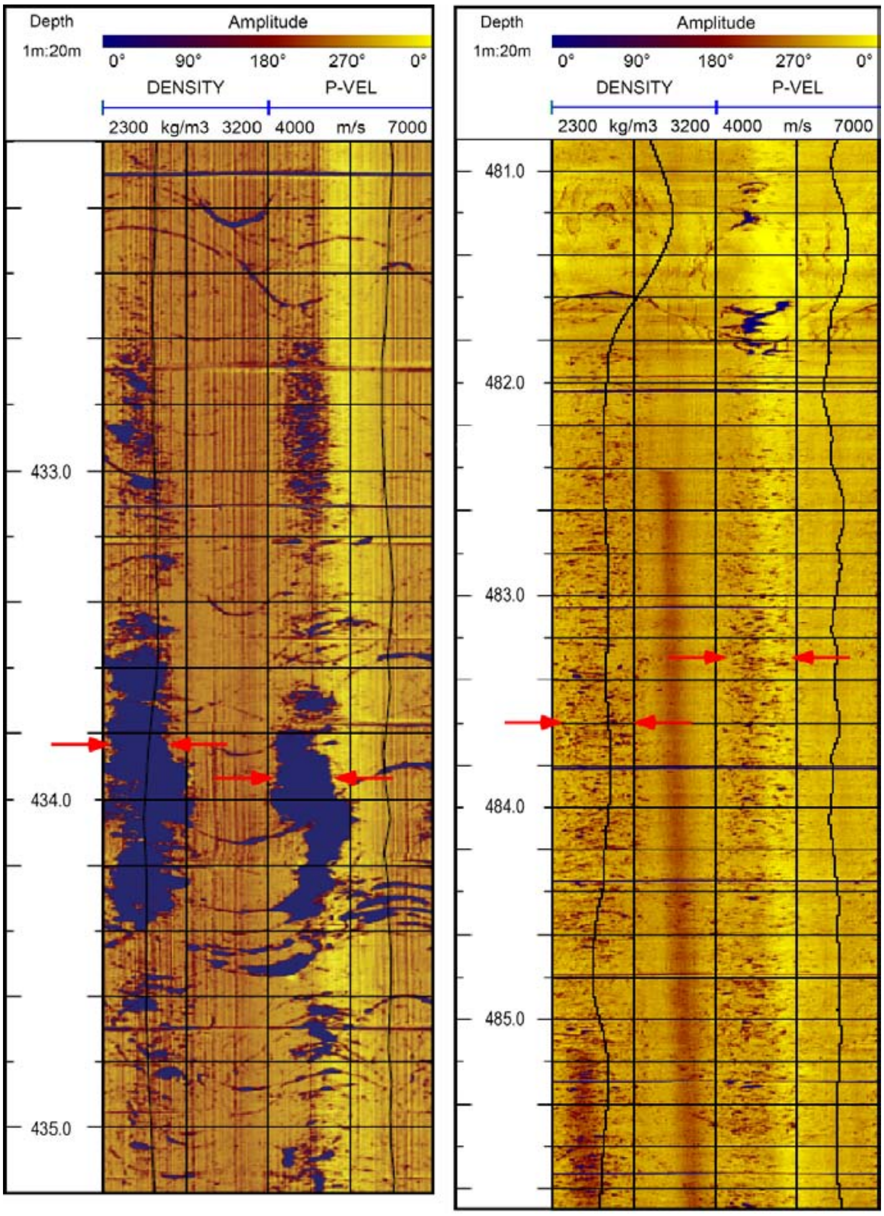

Figure A3-10. *Example of complementary methods for characterisation of the stress field. Results from acoustic televiewer logging showing stress-induced borehole breakouts in borehole KFM01B at Forsmark. At left: example of large sporadic breakout in the borehole Section 432.0–435.2 m borehole length (mbl). At right: stress- and temperature-induced micro-breakouts in the Section 480.8–485.9 mbl. Red arrows indicate breakout width.*

Laboratory tests of drill core samples are performed for determination of a number of mechanical properties of the intact rock as well as of rock fractures, e.g. density, tensile strength, compressive and shear strength, coefficient of thermal expansion, elastic properties (modulus of elasticity and Poisson's ratio) and the hydromechanical properties of fractures. Laboratory tests and analyses of drill core and cutting samples are done by outside, generally certified laboratories.

As far as **mechanical properties (on a large scale) of the rock mass** are concerned, it is usually not possible to test and determine them in the field. Instead, the mechanical properties of the rock mass are therefore determined with the aid of empirical relationships between the properties and some established rock classification system, mainly the RMR (*Rock Mass Rating*) and Q (*Tunnelling Quality Index*) systems. A prerequisite is that the rock volume is sufficiently large to contain four or more fracture systems. In the case of rock volumes with few fractures, however, there are no general and simple relationships.

A3.6 Thermal investigations

The *thermal conductivity* of the rock is of great importance for the function of the final repository, since it determines how densely the canisters can be emplaced in the deposition tunnels and thereby how much rock must be blasted out. To ensure that the bentonite in the deposition holes and the surrounding rock is not exposed to excessively high temperatures at any time, it is an advantage if the thermal conductivity of the rock is high. Like many other geo-related parameters, thermal conductivity varies depending on the scale on which it is regarded. There is considerable variation at the mineral level, but this variation is normally evened out on a larger scale. In certain rock types there is also considerable spatial variation within the rock, due to geochemical/mineralogical variations in the rock mass.

Thermal conductivity is measured on a centimetre scale in the laboratory. Moreover, a method has been developed for indirect determination of thermal conductivity by density logging, which provides an idea of the spatial variation on a decimetre scale. The theoretically most suitable scale for measurements in a final repository context is the volume that affects the maximum temperature of the canister, which occurs after 10–20 years. This volume is relatively great, and it would take an unreasonably long time to perform in situ measurements of thermal conductivity on this scale.

The most relevant measurement scale for studying variations of thermal conductivity in the rock mass in practice is about 3–5 metres. On this scale, an evening-out of properties has taken place, and a substantial reduction in variance can be expected. Measurements are largely lacking for this scale, leading to some uncertainty in the site descriptive thermal model. Verifying measurements on this scale should therefore be considered.

During the site investigation, SKB conducted a study aimed at selecting existing methods for measurement of thermal conductivity in situ on a relevant and practically feasible scale, or alternatively identifying the need for technical development of such methods. The work was focused on investigations from the ground surface, but also has relevance for underground measurements, even though certain modifications may be required for underground use. The study arrived at a recommendation for method development with the following two main lines:

1) single- or multiple-probe method for measurements on rock outcrops,
2) some type of heat source about 5 m in length, sealed off by packers, for measurements in deep boreholes.

A method for measurements on rock outcrops was developed during the site investigation, and field tests were conducted at both Forsmark and Laxemar, see Figure A3-11. The method could conceivably be applied in a tunnel at repository depth as well. In order for measurements according to point 2) above to be performed, the method needs to be developed.

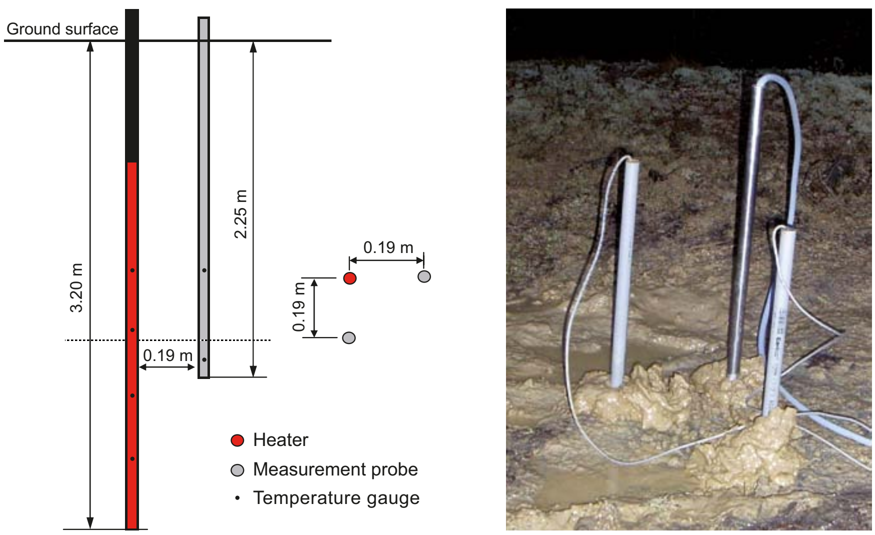

Figure A3-11. *Thermal field test conducted during the site investigations. The test setup consisted of a centre hole where heat was generated by an electric heater and two or more surrounding boreholes in which the temperature change was recorded.*

With regard to **thermal laboratory methods**, these methods, like methods for strength testing, are carried out by outside, generally certified laboratories.

A3.7 Hydrogeological borehole investigations

For determination in boreholes drilled from the ground surface of *hydraulic parameters* – primarily hydraulic conductivity and/or transmissivity, but also e.g. skin (i.e. flow losses in connection with pumping or water injection caused by the borehole or the test procedure), flow dimension, connectivity, natural groundwater pressure and flow and storage coefficient – *pumping tests* and *injection tests* (Figure A3-12), as well as *flow logging during pumping or under natural gradient conditions,* can be employed. The measurements can be conducted as full-hole tests or in packered-off borehole sections. These types of tests have been employed frequently during the site investigations, but also in an underground environment in e.g. the Äspö HRL.

A special form of flow logging is difference flow logging (Figure A3-13), which is a method based on decay (dilution) of induced thermal pulses in packered-off borehole sections. With this method, hydraulic conductivity/transmissivity can be determined for different section lengths along the borehole, down to very short intervals. Other parameters that are determined are hydraulic head, groundwater temperature and salinity and several geophysical parameters (point resistance, temperature and caliper values). The hydraulic characterisation is often performed down to a metre's section length and with overlapping technique to a decimetre's length over hydraulic anomalies for better characterisation. In another application, the same thermal measurement principle can be utilised for determination of the groundwater flow through the section under natural gradient conditions, as well as of the direction of the groundwater flow in the section, roughly related to the quadrants around the axis of the borehole. There is also another method for determination of groundwater flow under natural gradient conditions that is based on the principle of dilution of a nonsorbing tracer, see Sections A3.9 and A3.12.

Most of the aforementioned investigation methods can be used in both underground and surface holes. Due to the fact that boreholes situated below the groundwater table are under hydraulic pressure (Figure A3-13), the test method *outflow measurements in combination with pressure buildup tests* is also used. The method is often applied under ground and largely takes the place of pumping and injection tests. Hydraulic tests can also be carried out as *interference tests (cross-hole tests)* both above and below ground in cases where large rock volumes are to be characterised with respect to geometry, connectivity and other hydraulic properties.

Figure A3-12. *Determination of hydraulic parameters in surface boreholes by different methods. At left: pumping test in percussion borehole; at right: injection tests in cored borehole.*

Figure A3-13. *At left: Posiva's equipment for difference flow logging. At right: borehole under hydraulic pressure in Äspö HRL.*

Prominent characteristics of the Forsmark site descriptive model are low fracture frequency and low hydraulic transmissivity at repository depth, see Figure A3-14. These are generally favourable properties from the perspective of long-term safety. However, transmissivity within large rock volumes is so low that it is below the lower measurement limit for certain measurement methods. In the case of methods with a low lower measurement limit, the low permeability can lead to long test times if the transmissivity values are to be determined with high accuracy. The site investigations have shown that the opposite condition can also exist in the bedrock section down to about 150–200 m, i.e. that the hydraulic transmissivity is so high (cf. Figure A3-14) that it may lie beyond the upper measurement limit of ordinary measurement instruments.

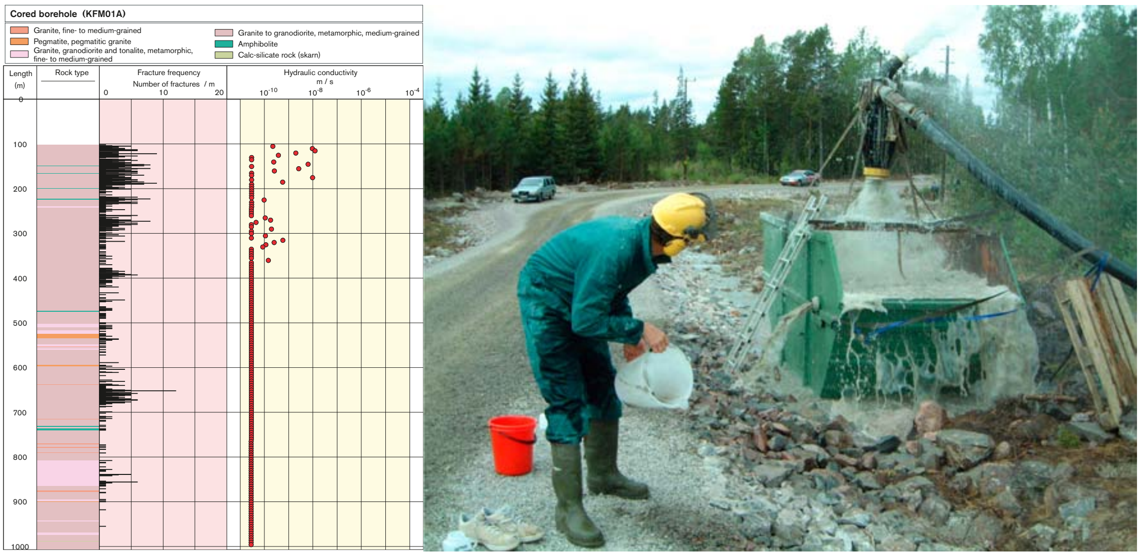

Figure A3-14. *Illustration of the contrast in hydraulic conductivity between the shallower and deeper parts of the bedrock within the candidate area at Forsmark for the final repository. At left: chart with rock type and fracture distribution as well as hydraulic conductivity along a 1,000 m long, nearly vertical cored borehole in the central part of the candidate area. Hydraulic conductivity lies at or below the lower measurement limit of the measurement instrument from about 350 m to 1,000 m, while it exhibits a number of high values down to about 200 m. The hydraulic conductivity in the Section 0–100 m, which was percussion-drilled to a large diameter, was determined by an alternative measurement method (capacity measurement at maximum drawdown) and proved to be very high (cf. figure at right). At right: drilling of percussion borehole at Forsmark in the immediate vicinity of the cored borehole illustrated on the left. A water inflow of about 1,000 l/min (at maximum drawdown) was encountered in a short fractured section at about 42–45 m.*

Different types of hydraulic tests performed during the preparation of a deposition area are judged to provide valuable information for evaluation of the existence and geometry of "large fractures". Here the sectioned pilot borehole for tunnels, as well as other types of investigation boreholes drilled from tunnel positions, can be utilised both as test boreholes (e.g. pump boreholes) and as observation boreholes for recording of pressure variations when pumping or drilling is being carried out in another borehole. Hydrogeological methods for long-term observations (monitoring) are presented in Section A3.12, "Monitoring".

A3.8 Hydrogeochemical investigations

Water sampling with subsequent laboratory analyses is done for determination of hydrogeochemical parameters. Simpler physical-chemical characterisation of surface water and groundwater, above all determination of *water temperature, pH and electrical conductivity*, should be done directly in the field with measurement instruments adapted for field use. During the site investigations, water samples were collected in the different types of boreholes that were drilled, but also in surface water, i.e. in the Baltic Sea, lakes and wetlands, as well as of precipitation (see examples of water sampling in different environments in Figure A3-15). Water samples from pore water in sediments and from the rock matrix in drill cores have also been analyzed. A well functioning method for sampling of matrix pore water from drill cores (a procedure that is very sensitive to disturbance) was developed during the site investigations. After initial hydrochemical sampling campaigns during the site investigation in boreholes and different types of surface water, a number of points were selected for periodic sampling/analysis within the framework of the *hydrochemical/hydrogeochemical* monitoring programme, see further Section A3.12.

SKB has an own-developed mobile system (Figure A3-16) with sampling and laboratory unit for advanced sampling in cored boreholes drilled from the surface, so-called *complete chemical characterisation* in packered-off borehole sections. In addition to a specially-designed pump unit and a well equipped chemistry laboratory, the system offers continuous *online recording* of some sensitive parameters. This is done by two measurement cells (*Borehole Chemmac* and *Surface Chemmac*), through which the water is conducted in an unbroken line on its way up to the chemistry laboratory. These cells record *Eh (redox potential), pH, water temperature, dissolved oxygen* and *EC (electric conductivity),* the last two parameters only in *Surface Chemmac*, while *Borehole Chemmac* also measures the *pressure in the borehole section*.

Figure A3-15. *Top row: hydrochemical field sampling and analysis during the site investigation at Forsmark in, from left, a deep borehole, a brook and a lake. Bottom row: groundwater sampling in underground environment (Äspö HRL).*

Figure A3-16. *SKB's mobile chemistry laboratory.*

Surface Chemmac is equipped with commercial electrodes and sensors and is placed in the ground unit of the sampling equipment, where the measurement is performed on the pumped-up groundwater. The electrodes are not designed for high water pressures, and it has proved difficult to find electrodes on the commercial market designed for the high hydrostatic pressures that prevail in deep boreholes. For *Borehole Chemmac*, which is intended to be used in boreholes down to about 1,000 m below the ground surface, and which consists of a flow-through cell down in the borehole with associated measurement electronics, SKB has therefore developed its own electrodes with accessory equipment for Eh, pH and temperature.

In an underground environment, sampling is facilitated by the fact that the boreholes are under pressure (Figure A3-13), which means that pumping is generally not necessary during sampling. Moreover, contaminants from drilling, such as flushing water and drill cuttings, are transported more efficiently out of the borehole with the groundwater, at least when the water-bearing fractures have relatively high hydraulic transmissivity, and if the borehole is allowed to stand open for some time after drilling.

Even in the case of complete chemical characterisation in an underground environment, detailed characterisation will require *online recording* of the aforementioned sensitive chemical parameters. One possibility is to use a subsequently developed portable instrument, see Figure A3-17, which has been used in the investigations in the Prototype Repository at the Äspö HRL, and which is designed for the water pressures that prevail at repository depth. The measurement cell in this instrument, which is located outside the borehole, can measure the same three parameters as *Borehole Chemmac* (Eh, pH and temperature), and a high water pressure is maintained in the cell by restricting the water flow. Great importance was attached in the design of this instrument to the choice of material for all components that come into contact with the groundwater. For example, all water hoses consist of a plastic called PEEK (*PolyEtherEther Ketone*), a material that minimises the diffusion of oxygen, which is of great importance for the Eh measurements.

SKB has defined *five chemistry classes* for water analyses, where class 1 involves the least extensive and class 5 the most extensive analyses. The latter includes, in addition to laboratory determinations (batch measurements) of pH and Eh, the main components (TDS, Na, K, Ca, Mg, S, Sr, Si, HCO_3^-, SO_4^{2-} and Cl^-), complements of these (Fe, Li, Mn, DOC, Br, F^-, I, HS^- and NH_4^+), a number of trace elements (e.g. rare earth metals), and also many stable and radioactive isotopes. In addition, *special analyses of dissolved gases, colloids and humic and fulvic acids* are performed in connection with complete chemical characterisation /SKB 2001/.

Figure A3-17. SKB's portable measurement instruments for underground measurement of Eh, pH and groundwater temperature. All water hoses are made of PEEK.

Fracture mineral analyses complement the picture of the present and past chemical composition of the groundwater, as well as of the processes that have affected it. For example, the presence or absence of calcite minerals indicates whether infiltration of surface water has been heavy or not, while the occurrence of iron hydroxides in combination with the absence of pyrite shows how far down oxidizing water has circulated. These examples illustrate the fact that fracture mineral analyses, which constitute a natural bridge between geology and hydrogeochemistry, provide a better understanding of the hydrogeochemical conditions.

Regarding SKB's development plans for sampling and analysis methods in the hydrogeochemical area, see Section 7.3.6.

A3.9 Investigations concerning transport properties of the rock

Characterisation of the *transport properties of the rock* is done using field methods in combination with laboratory analysis of drill core samples. **The field methods** comprise *resistivity measurements for determination of the formation factor (diffusivity)* and *tracer tests in boreholes*, which can be conducted as single-hole or cross-hole tests, above or below ground. SKB has developed a special equipment unit called a dilution probe for SWIW (*Single Well Injection Withdrawal*) tests, but special equipment has also been developed for cross-hole tests. Tracer dilution measurements can be used to determine groundwater flow under natural gradient conditions, along with transport properties such as flow porosity, dispersivity, retardation factor, sorption coefficient, matrix diffusion coefficient, etc.

Technical development of laboratory methods is currently under way, and a possible in situ application of the methodology for determination of matrix diffusivity will also be investigated, see Section 7.3.7.

The laboratory methods mainly include *determination of diffusion properties, porosity and sorption on drill core pieces* (crushed rock is mainly used in the case of sorption) and *resistivity measurements on rock samples for determination of the formation factor (diffusivity)*. Along with through-diffusion measurements, these serve as guideline values for equivalent borehole measurements. From a planning viewpoint, it is important to take into account the often very long lead times between the sampling occasion and the finished report of results for these types of analyses.

A3.10 Mapping of underground openings

This category of investigations plays a central role in the detailed characterisation programme. *Geoscientific documentation of all tunnels, shafts and other underground openings* is one of the *process-oriented activities* that will require the most time and resources of all individual investigations. Due to the fact that underground rock surfaces will increasingly be exposed as the construction of the final repository progresses and eventually be quite large in area, there will be much greater opportunities to study the rock's structure in three dimensions than when, as during the site investigation, only surface information was available in combination with drill cores and other rock samples. The ramp and shafts will offer an opportunity for continuous geological documentation of rock surfaces of considerable area from the ground surface to repository depth. Tunnel walls, ceilings and floors at repository depth will be of even greater extent. Even though the geological site descriptive model for Forsmark is considered robust, the tunnel documentation will lead to a considerably better understanding of details in the geological structure of the repository volume.

Aside from the geological documentation, which provides the basis for the conceptual geometric modelling which is the point of departure for other geoscientific modelling, the exposed rock surfaces in the underground openings will also enable the rock mechanical, hydrogeological and hydrogeochemical descriptions of the repository volume to be made much more detailed than was permitted by the above-ground investigations. However, it is necessary to take into account the fact that the rock in a zone near the tunnel perimeter is more or less mechanically damaged by the excavation process and hydraulically disturbed within a distance of about one tunnel diameter from the tunnel due to rock stress redistribution, two-phase flow effects, etc.

SKB has experience of tunnel documentation mainly from the construction of, and subsequent activities at, the Äspö HRL. Via its cooperation with Posiva, SKB can also learn from the experience of tunnel documentation at ONKALO. The tunnel wall characterisation performed in conjunction with the construction of the Äspö HRL in the latter part of the 1980s included the following points /Almén and Stenberg 2005/:

- Photographic documentation (Figure A3-18).
- Geological mapping (Figure A3-19).
- Rock mechanical documentation.
- Hydrogeological mapping.
- Hydrogeochemical sampling.

Information from the geological tunnel documentation was compiled for analysis and documentation in the manner exemplified in Figure A3-20. The hydrogeological and hydrogeochemical documentation was presented with a similar layout.

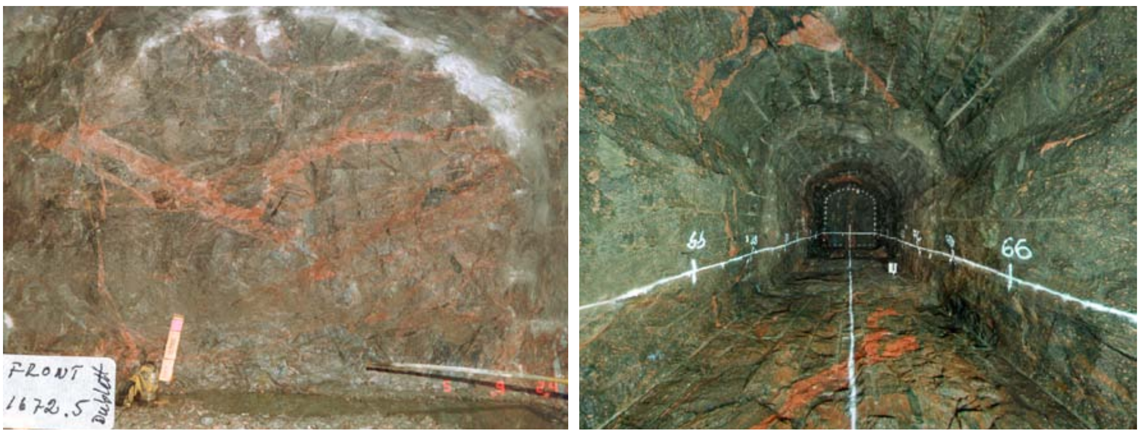

***Figure A3-18.** At left example of photographic documentation of the tunnel face during construction of accesses to the Äspö HRL, and at right of a whole tunnel section (face, ceiling, walls and floor) during tunnelling of the TASS tunnel in the Äspö HRL.*

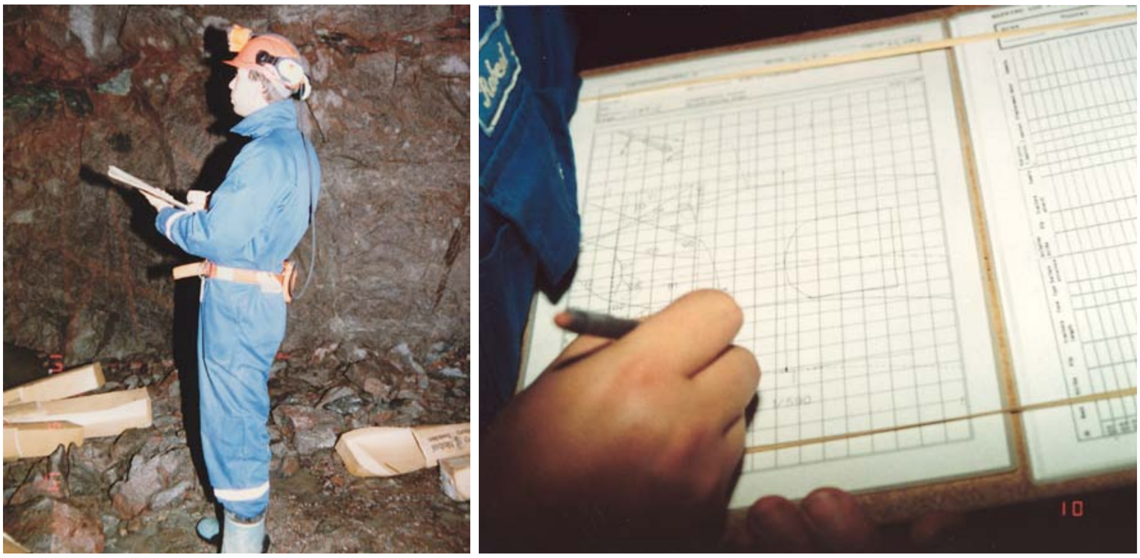

Figure A3-19. *Conventional geological tunnel mapping in the Äspö HRL. During geological mapping in the final repository, a mapping (field) computer will take the place of paper and pen.*

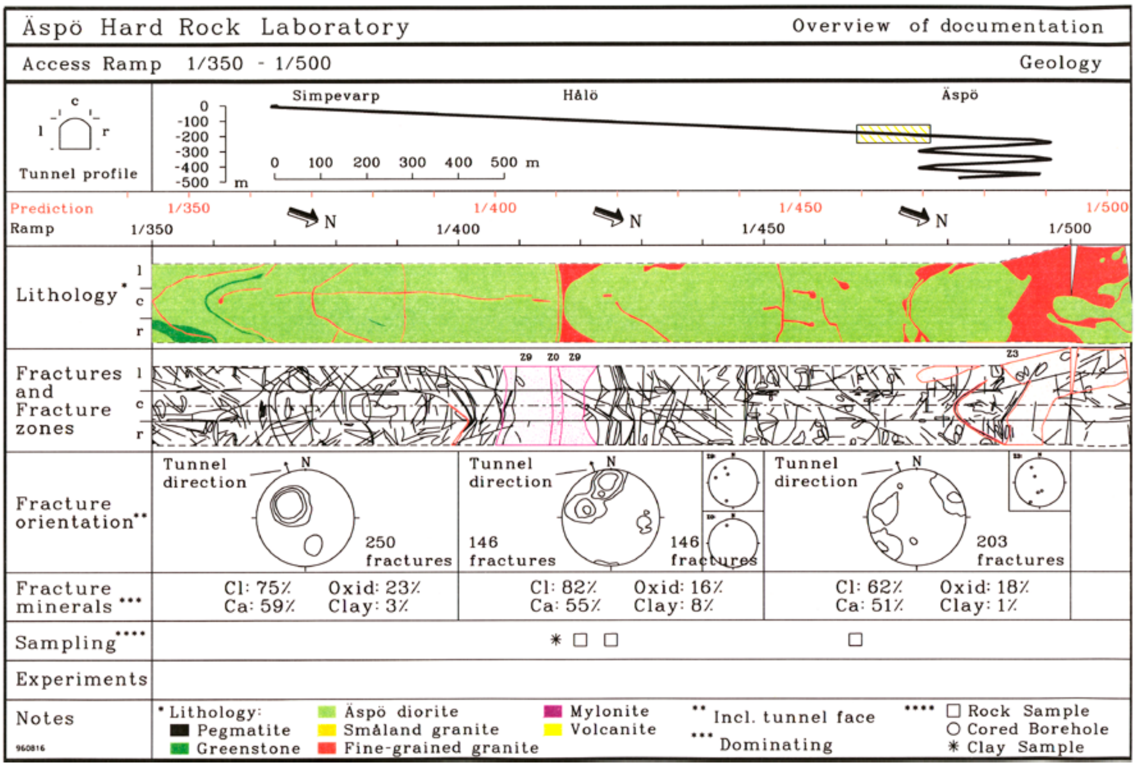

Figure A3-20. *Example of presentation layout for geological data from a 150 m long tunnel section from the construction of the Äspö HRL.*

In principle the same type of documentation will be prepared during the construction of the final repository. One difference, however, is that a tunnel mapping system called RoCS (*Rock Characterisation System*), which is currently under development (see Section 7.3.1), will be employed. With this system, a digital mapping record is first created by photogrammetric means, after which the information from the actual mapping is entered into a field computer which the mapping geologist brings along on each mapping occasion. The system enters the position and spatial orientation of the geological structures that appear three-dimensionally (i.e. on more than one of the mapping surfaces) and photographically documents, for each blasting round, all rock surfaces except the floor, i.e. face, walls and ceiling.

The tunnel floor is more or less concealed by shot rock, drill cuttings, etc and can therefore not be easily mapped. Once individual deposition tunnels have been completed, however, the floor will also be thoroughly cleaned and mapped according to the same principles as other rock surfaces.

Rock mechanical information can for the most part be obtained from the geological dataset, but if necessary field checks can be made with a specific focus on rock mechanical conditions. As regards hydrogeological and hydrogeochemical tunnel documentation, the mapping system offers measured positions of hydraulically conductive structures, but this information must be combined with inflow measurements and groundwater sampling.

The exact logistics associated with the tunnel documentation of the final repository project, for example whether the different geoscientific disciplines will work in synchrony or not and similar questions, belongs to the detailed planning work which remains to be done, but which must be finished before construction of the final repository begins with ramp and shaft driving.

The documentation layout has not been established either, but several variants of data presentations will probably be needed to meet the needs of different data users. It is essential that the mapping system and the databases linked to it have the capacity to quickly produce quality-assured output data, both raw and processed data on different scales, and that it has the flexibility to create presentations where data can be selected and combined in different ways to meet different types of analysis and presentation needs, see also Section 7.4.

An activity that is in need of data with a high information potential is *single-tunnel interpretation*. By this is meant integrated interpretation of information collected in conjunction with pilot drilling, probe drilling, rock excavation and subsequent geoscientific characterisation of the finished tunnel, cf. Figure A3-3. The analyzed information is primarily geological (lithology, ductile structures, fracture intensity, fracture properties, minor zones, "large fractures", etc) and hydrogeological (inflows, characterisation of inflow points and results of hydraulic tests in pilot and probe holes and from recording of pressure responses in pilot boreholes). Additional information may consist of hydrogeochemical data plus parameters collected from measurements while drilling (MWD) and tunnelling. Despite the difference in scale, single-tunnel interpretation is comparable to single-hole interpretation of borehole information, a method that has been employed frequently during the site investigation with good results.

The more or less continuous, process-oriented tunnel documentation will be complemented by *activity-oriented investigations*. For example, fracture mineral mapping on the tunnel scale will be carried out in certain tunnel sections, along with special studies of the relationship between rock type composition/distribution and thermal properties. Other investigations will be aimed at identification and characterisation of "large fractures". This category mainly includes geophysical surveys, primarily seismic refraction and seismic reflection, but also resistivity and GPR (*Ground Penetrating Radar*) surveys.

The same type of geophysical surveys might be employed for characterisation of the EDZ (see definition in Section 4.5.2), whose size and properties are dependent on both the properties of the rock and the rock excavation method. The EDZ will be characterised hydraulically if necessary to verify that the design premises are fulfilled. This task is primarily linked to the development of reference methods for rock excavation in tunnels and shafts so that related requirements on the underground openings are met, in this case the hydraulic conductivity of the EDZ. Such measurements are not expected to be able to be performed during the construction of the facility as a continuous verification measure, however, since a complex measurement setup is probably needed for this.

A3.11 Non-borehole-related surface investigations

This category of investigation will be of limited scope during construction and operation of the final repository. Some examples of possible investigation measures and methods are given below.

Traditional geological and geotechnical assessments of Quaternary deposits will be made in conjunction with excavations in locations for the access ramp and for ventilation, skip and passenger shafts. Furthermore, the exposed rock surfaces will be mapped with respect to rock types, fractures and ductile structures.

Surface ecological investigations beyond those included in monitoring (see next section) are not expected to be of great scope, but will be carried out as needed. Supplementary investigations of present and future discharge areas for deep groundwater may be conducted to reduce certain remaining uncertainties. Furthermore, point inventories and investigations of flora and fauna, but also of sediments and soils, may be necessary. The effects of possible groundwater draw-down in, for example, wetlands may need to be investigated. Supplementary investigations of wetlands planned to be used as broad irrigation lands for treated waste and drainage water from the facility may be needed. There must also be preparedness for other ground-based surface investigations that may be occasioned by new questions or deficiencies discovered in the site descriptive model.

A3.12 Monitoring

A system for monitoring (see definition in Section 4.2.3) of geoscientific and surface ecological parameters at Forsmark was gradually built up during the site investigation /SKB 2007/ so that time series could be generated. The monitored parameters are characterised by a certain time- and place-dependent variability. The monitoring has a two-fold purpose.

The first purpose is to gain better knowledge of underlying, often complex cause-and-effect relationships by studying the patterns of variation of the monitored parameters. This increases the precision in the description of the site-specific conditions and provides a better body of data for modelling of important processes. This improves our understanding of the site. An example is groundwater monitoring where groundwater levels and pressures at different depths are measured in packered-off boreholes, see Figure A3-21. Level monitoring is of great importance for gradual accumulation of a hydrogeological understanding of the repository rock and (later) the environmental effects of the underground facility, including the impact on the soil layers. This recording of data during construction of the repository must be combined with an equally thorough recording of planned and unplanned events that can affect not only the tunnelling work, but also the pressure situation. Examples of such events are drilling or opening and closing of boreholes in conjunction with water sampling or hydraulic tests.

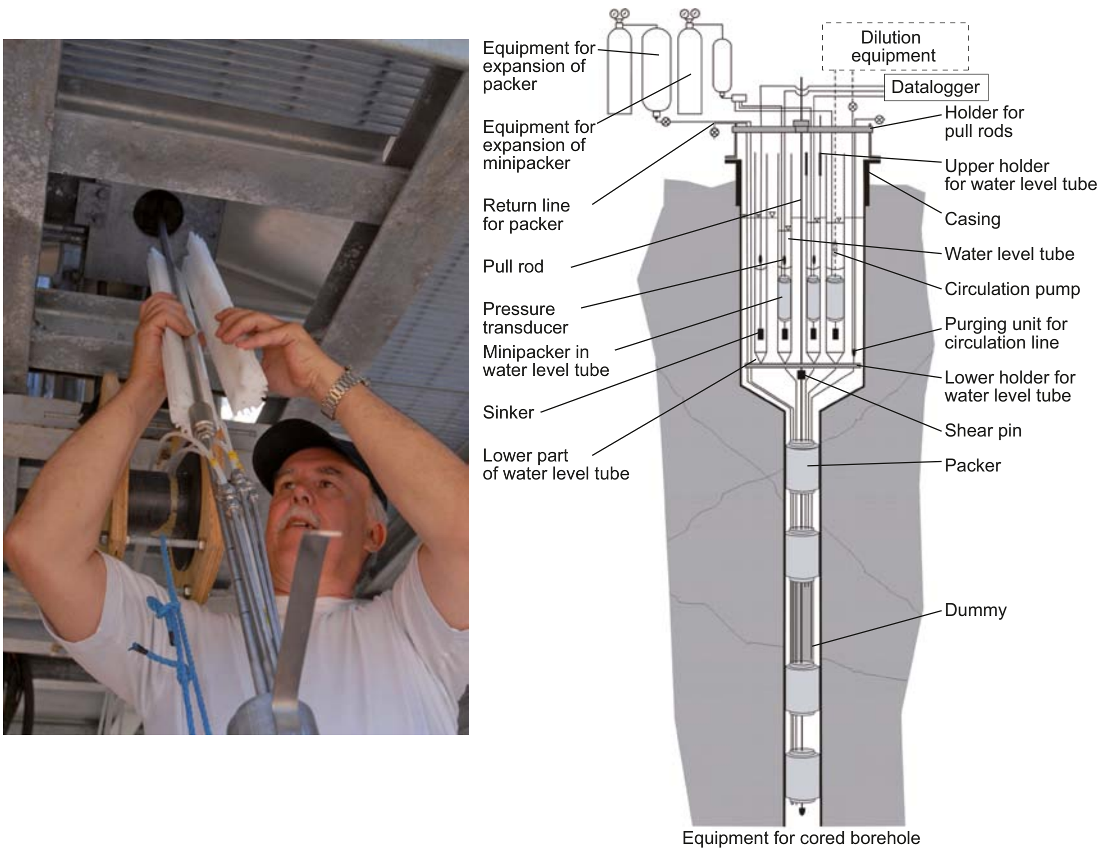

Figure A3-21. *At left: installation in deep cored borehole of the equipment for monitoring of groundwater pressure at different levels and for groundwater sampling that is illustrated at the right.*

Recording of pressure responses during drilling can be utilised for interpretation of connectivity and barrier effects in the repository area, as well as for analysis of the geometry of conductive structures /Winberg et al. 2000, Andersson et al. 2002/. Similar recording in conjunction with tunnelling has been essential in interpreting the occurrence and geometry of conductive structures at the Äspö HRL, where the inflow of groundwater to different tunnel and shaft sections as well as the electrical conductivity of the groundwater has also been monitored for many years, see Figure A3-22. Figure A3-23 shows the location of all cored boreholes drilled from the ground surface at Forsmark in which monitoring equipment for recording of groundwater pressure was installed during the site investigation.

The second purpose of the monitoring system is to provide a tool for determining the impact of the final repository project on the surrounding environment. Because monitoring involves recurrent measurements over a given period of time, longer or shorter data time series are generated. For the purpose of environmental monitoring, it is necessary to generate a time series before the environment-impacting activity begins in order to describe the initial state (*baseline*) in a credible manner. The present report does not deal with matters relating specifically to environmental monitoring, but it is important to document when conditions have been undisturbed (baseline) versus disturbed. This information is also needed when monitoring is utilised for site descriptive modelling. Three important phases can be identified for the part of the monitoring system that began to be established during the site investigation:

A. The site investigation phase, when the system was built up and generation of time series began. Certain monitoring points were established as early as 2002, so time series of 4.5–5 years had already been achieved for these points during the site investigation period. However, activities such as drilling and pumping led to certain disturbances of groundwater levels and hydrogeochemical conditions, at least in the local environment of the borehole in question while the activity was under way.

B. The phase from the conclusion of the site investigation at mid-year 2007 until the start of repository construction, a period of about 9–10 years, when outside disturbances will probably be minimal. This period is therefore of great importance for final establishment of a *baseline* for a number of parameters.

C. The phase during the construction and operation of the final repository, when the monitoring system furnishes data for continued modelling and comprises the tool by means of which the environmental impact of the final repository project can be quantified and related to the then well documented baseline conditions. In this context it is important to be able to differentiate between natural changes of both a reversible and an irreversible nature and changes due to human activity.

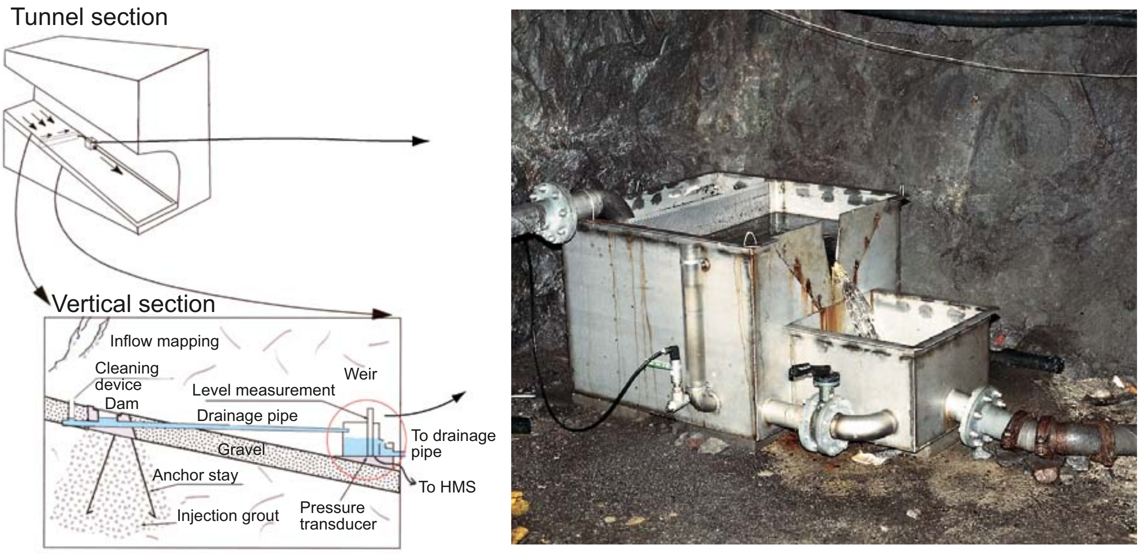

Figure A3-22. *Measuring weir in Äspö HRL for monitoring of groundwater flow and electrical conductivity. The drawings at the left illustrate the design principle.*

Figure A3-23. *Map showing the location of the 25 cored boreholes at Forsmark where monitoring equipment for recording of groundwater levels and pressures was installed during the site investigation. Many of these boreholes also have equipment for hydrogeochemical monitoring and for groundwater flow measurements. Similar (but simpler) equipment is installed in 36 percussion boreholes and some 60 boreholes in Quaternary strata.*

The planned scope of the monitoring programme at Forsmark is described in Section 4.2.3, Table 4-1. Table A3-1 below shows some of the same information, but more strictly subdivided into disciplines and more method-oriented. The table shows which monitoring is performed in boreholes and which is independent of boreholes, plus whether the monitoring is conducted with continuous recording of results or in the form of intermittent measurement and sampling campaigns. In the case of continuous recording, the scanning frequency can vary widely for different methods.

Most monitoring activities in the table were initiated during the site investigation, i.e. during the period 2002–2007. An exception is seismic monitoring in a local network, which is planned to be installed in good time before the start of tunnelling.

At present there is one seismic monitoring station belonging to SNSN (*the Swedish National Seismic Network*) within the Forsmark site investigation area, and another station nearby (on Gräsö). Low magnitudes of both natural and induced seismic activity in the Earth's crust can be recorded by these stations. This part of the monitoring at Forsmark is planned to be complemented by the installation of a local seismic network with the capacity to record considerably lower magnitudes than the stations in the national network are capable of, see further Sections 4.2.3 and 7.3.8. One of the purposes of seismic monitoring is to determine the seismic stresses to which the final repository may be exposed. The monitoring also allows the effects of blasting in terms of stress redistribution to be studied. An earthquake database is being built up in this way, and measurement data can be analyzed and contribute to a better understanding of the response of the near-field rock to the tunnelling, which also reveals more about the properties of the stress field.

Table A3-1. Planned scope of the monitoring programme in the detailed characterisation programme – method overview.

Discipline	Monitoring in boreholes	Other monitoring	Methodology
Geology/ geophysics	3) Seismic monitoring within a local seismic network.	1) Monitoring of horizontal movements in the Earth's crust. 2) Seismic monitoring within the Swedish National Seismic Network (SNSN).	1) Continuous recording via GPS receiver of movements at seven ground-based thermally and physically stable monitoring stations. 2) Recording of natural and induced seismic activity down to a magnitude of 0.0. 3) Recording of natural and induced seismic activity with lower magnitudes than are possible with the national network.
Meteorology		1) Monitoring of weather parameters – precipitation – air temperature – barometric pressure – wind speed – wind direction – relative humidity – global radiation. 2) Monitoring of snow depth, water content of snow and time of ice freeze-up/break-up.	1) Continuous recording at high scanning frequency of all parameters except precipitation. The accumulated total precipitation for each half hour is recorded. 2) Snow and ice measurements are done manually.
Hydrology		1) Monitoring of surface water levels including the sea level in the Baltic Sea. 2) Monitoring of surface water runoff, EC (electrical conductivity) and temperature of surface water.	1) Continuous recording at a number of monitoring stations. 2) Continuous recording at a number of monitoring stations. Runoff is monitored by two measurement flumes per station.
Hydrogeology	1) Monitoring of groundwater levels in Quaternary strata. 2) Monitoring of groundwater pressure in the bedrock. 3) Monitoring of seepage into deposition holes.	4) Monitoring of groundwater inflow to the facility and of the electrical conductivity of the groundwater in connection with e.g.: – point seepage – seepage into tunnels or tunnel sections – seepage into the entire facility.	1) Continuous recording of groundwater levels and pressures in a large number of soil wells. 2) Continuous recording of groundwater levels and pressures at different depths down to about 1,000 m in a large number of cored and percussion boreholes drilled from the ground surface and, when tunnelling starts, a varying number of underground boreholes. 3) Method development is required. 4) Methodology probably similar to that applied in the Äspö HRL with measurement weirs and associated measurement systems.
Hydrogeo-chemistry	1) Monitoring of the chemical composition of the water in Quaternary strata. 2) Monitoring of the chemical composition of deep groundwater.	3) Monitoring of the chemical composition of the precipitation. 4) Monitoring of the chemical composition of the surface water.	1) Recurrent sampling campaigns in some 20 or so soil wells and private wells. 2) Recurrent sampling campaigns in a large number of cored and percussion boreholes and, when tunnelling starts, a varying number of underground boreholes. 3) Recurrent sampling campaigns at one monitoring station. 4) Recurrent sampling campaigns at a number of measurement points in lakes, sea bays and surface watercourses.
Transport properties of the rock	Monitoring of groundwater flow under natural and disturbed conditions.		Recurrent measurement campaigns in a large number of cored and percussion boreholes drilled from the ground surface, and, after the start of tunnelling, in some underground boreholes as well.
Surface ecology	1) Monitoring of hydrogeo-chemical parameters in Quaternary strata with a focus on chemical parameters of importance for the surface system, such as nutrients.	2) Monitoring of hydrochemical parameters in surface water with a focus on chemical parameters of importance for the surface system, such as nutrients. 3) Monitoring of birds. 4) Monitoring of the demographics and reproduction of the elk population.	1) Recurrent sampling campaigns in a large number of soil wells. 2) Recurrent sampling campaigns at a number of measurement points in lakes, sea bays and surface watercourses. 3) Annual inventory. 4) Annual inventory.

A3.13 Geodetic methods

The coordinates of thousands of physical objects and data points in tunnels and boreholes will be measured during detailed characterisation. In addition, a large number of position determinations will be made for as-built plans and building activities. It is very important that these three-dimensional coordinate determinations be done with high precision, since the quality of the conceptual geoscientific models is highly dependent on correct determination of the positions of the included data points. The geodetic methods that are used for this purpose and the instruments to be used must meet SKB's requirement specifications. Three main activities will employ geodetic methodology:

1) Coordinate measurement and levelling of physical objects such as borehole ends with casing projections, measurement weirs, studs for convergence measurement, etc.
2) Photogrammetric documentation of deposition holes and rock caverns.
3) Measurement of borehole deviation (which in a broad sense can be included in geodetic methodology, even though the methods for this were dealt with in Section A3.3 under the heading "Borehole investigations connected with drilling").

Point 2) mainly refers to coordinate measurement to verify that the geometric specifications for deposition holes (volume, diameter, straightness, etc) and for tunnels (volume, cross-sectional areas, breakouts) have been satisfied so that bentonite buffer and backfill can fulfil its given barrier function (see Appendix 1). Measurement methods may be based on total station or laser.

It is of great importance that an efficient system be created for designation of boreholes, weirs and all other points and profiles whose coordinates will be measured, in accordance with the planned database structures.

One aspect that should be mentioned in this context is that the national planar coordinate and height systems in Sweden are currently being replaced. The former systems, RT 90 for planar coordinates and RHB 70 for heights, which were used by SKB during the site investigations, will generally be replaced by SWEREF 99 and RH 2000, respectively. SKB also intends to switch to the new systems. In this context, all coordinates determined in the old systems during the site investigations must be converted to the new systems. This involves a great deal of work, which should be started immediately. SKB has therefore initiated a feasibility study for the purpose of analyzing how this work can best be carried out.

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