# BACKGROUND REPORT TO RD&D-PROGRAMME 92

# Treatment and final disposal of nuclear waste

## Äspö Hard Rock Laboratory

September 1992

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# FOREWORD

The Act on Nuclear Activities (SFS 1984:3) prescribes in Section 12 that a programme shall be prepared for the comprehensive research and development and other measures that are required to safely handle and finally dispose of the radioactive waste from the nuclear power plants. The responsibility lies primarily with the owners of the nuclear power plants. These owners have commissioned SKB to prepare the prescribed programme. According to Section 25 of the Ordinance on Nuclear Activities (SFS 1984:14), this programme shall be submitted to the National Board for Spent Nuclear Fuel in the month of September every third year.

The purpose of this third programme is to fulfil the above obligations.

The programme is presented in one main report and three background reports. The programme is called RD&D-Programme 92, where RD&D stands for Research, Development and Demonstration. The reason for the change of name compared to previous R&D programmes is to underscore the fact that, starting with the work at the Äspö Hard Rock Laboratory and the plans presented in this programme, the emphasis of the programme has been shifted towards demonstrating different parts of the selected disposal system. The main report describes the programme in its entirety. This background report provides a more detailed presentation of the work at the Äspö Hard Rock Laboratory. The other background reports deal with the RD&D planned for the siting of a deep repository and non-Äspö-related RD&D projects during the period 1993-1998.

Stockholm, September 1992
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# 1 INTRODUCTION

## 1.1 BACKGROUND

The scientific investigations within SKB's research programme are a part of the work of designing a deep repository and identifying and investigating a suitable site.

A balanced appraisal of the facts, requirements and assessments presented in connection with the preparation of R&D-Programme 86 /1/ led to the proposal to construct an underground research laboratory. This proposal was presented in the aforementioned research programme and was very positively received by the reviewing bodies.

In the autumn of 1986, SKB initiated the field work for the siting of an underground laboratory, the Äspö Hard Rock Laboratory, in the Simpevarp area in the municipality of Oskarshamn. At the end of 1988, SKB arrived at a decision in principle to site the facility on southern Äspö about 2 km north of the Oskarshamn Nuclear Power Station. After regulatory review, SKB ordered the excavation of the access tunnel to the Äspö Hard Rock Laboratory to commence in the autumn of 1990. In conjunction with the tunnelling work, which has now (September 1992) reached a depth of more than 200 m, a large number of investigations have been carried out.

This background report to SKB's RD&D-Programme 92 is based on the previous background reports on the Äspö Hard Rock Laboratory within R&D-Programmes 86 and 89 /2/. The report provides a general background and presents goals, project's results obtained to date and future work. Compared to the previous background reports, more space is devoted here to experiment planning and the future demonstration programme.

## 1.2 THE ÄSPÖ HARD ROCK LABORATORY AND SITING OF THE DEEP REPOSITORY FOR DEMONSTRATION DEPOSITION

Since the end of the 1970s, SKB has carried out comprehensive studies of the geological conditions on many sites in Sweden. Investigations have been carried out from the surface and in boreholes down to a depth of 1 000 metres on many so-called study sites. These site investigations are summarized in a background report to this RD&D-Programme 92 (Siting of a deep repository). Furthermore, extensive work has been carried out at the Stripa Mine within the framework of the international Stripa project. Special research projects focussing on the properties of fracture zones have also been carried out, among other places at the Finnsjön study site and within the Lansjärv project. The reader is referred to SKB's Technical Reports for an account of the results of these studies. In summary, these studies show that good prospects exist at many sites in Sweden for finding the geological conditions for siting a deep repository. The siting should therefore not be governed primarily or solely by the geological conditions.

The work leading up to the disposal of all nuclear waste in Sweden in a sealed deep repository is planned to be carried out in two main phases: Demonstration deposition and final disposal. Altogether the work extends over a period of more than 60 years. The decision to take the step to final disposal will not be taken until after completed demonstration deposition, evaluation of the results and consideration of other alternatives. These decisions lie in time after the year 2010.

The siting process imposes different demands on background data in different phases. A well-characterized rock volume at the Äspö Hard Rock Laboratory provides opportunities for testing the application and limitations of different theories and models on different scales. Similarly, different parts of the repository can be demonstrated and tested under realistic conditions in rock.

In an early phase, it is above all necessary to demonstrate, on the basis of pre-investigations, that the site can offer rock volumes with low water flux, favourable chemical conditions and mechanical stability. As the decision-making process proceeds and as the predictive models and the safety assessments become more detailed, specific demands will be made on more detailed information. The availability of well-founded and site-specific data from the Äspö Hard Rock Laboratory will make it possible to carry out and evaluate these predictive models and safety assessments in preparation for the investigations that will be conducted for the deep repository.

The Äspö Hard Rock Laboratory is coordinated with the siting process. To meet the requirements of the siting programme, for example, certain stage goals have been formulated for the laboratory, see further section 2.3. These stage goals govern the structuring of the RD&D-programme for the Äspö Hard Rock Laboratory.

# 2 GOALS

## 2.1 GENERAL MOTIVES

Investigations of potential repository sites – study sites – carried out thus far have only involved measurements on the ground surface and in boreholes. Beyond this, investigations have been performed in and from tunnels at Stripa and in conjunction with certain underground excavation works for other purposes. There is a need to directly verify the results of surface and borehole investigations with systematic observations from shafts and tunnels down to the depth of a future deep repository. The construction of the Äspö Hard Rock Laboratory provides excellent opportunities for such verification.

The detailed characterization of a candidate site that is planned for the latter half of the 1990s will include investigations of the rock from shafts and tunnels at repository level. This detailed site characterization includes the field surveys and analyses that will provide final confirmation of the suitability of a selected site for deep disposal of long-lived and high-level radioactive waste. The investigations will also furnish sufficient data for adaptation of the repository to the selected site and for an assessment of the long-term safety of the adapted repository. This assessment will be included in a siting application and demonstrate that the site fulfils the requirements of the Act on Nuclear Activities (KTL) and the Act Concerning the Management of Natural Resources (NRL). Some of the technology and methods for executing such investigations have been developed and tried at Stripa. Since Stripa is an abandoned mine, however, not all aspects of the technology can be tried there. Trials in a previously undisturbed area, at the Äspö Hard Rock Laboratory, will provide further opportunities to refine and perfect the methods before they are used "for real".

A central and difficult problem in the assessment of the long-term safety of the repository is the flow of groundwater in the rock's fracture system and the associated transport of substances (radionuclides) dissolved in the groundwater. Very extensive efforts have been and are being made to shed light on this problem. The continued research should above all be devoted to tying together and completing the picture that has been obtained through the investigations performed to date at different places. An initial such tying-together attempt has been made within the framework of phase 3 of the Stripa project. In preparation for the siting of the deep repository, similar tying-together attempts need to be made on a larger scale to obtain more experimental data to support the long-term safety assessment. Such a large-scale test is currently being carried out at the Äspö Hard Rock Laboratory.

The rock volume nearest a waste canister – the near field – is of great importance in preventing the dispersal of radionuclides. Research should therefore be aimed at increasing our understanding of processes in the near field. This can be done through experimental activities and on a full scale in the Äspö Hard Rock Laboratory.

Once a fundamental design for the deep repository has been chosen, the different parts included in this system need to be tested. It is of particular importance to test and demonstrate the interaction between engineered barriers and rock in as realistic an environment as possible. This will primarily involve long-term tests and demonstration tests on a full or representative scale. "Destructive" testing may also be required. This is yet another motive for building the Äspö Hard Rock Laboratory.

Prior to the construction of the deep repository, it is necessary to develop and verify the methods and the technology that are needed to build tunnels and repository chambers, to determine exactly where the waste is to be emplaced, to handle the waste in the rock, to deposit the waste in the intended location and to backfill and seal the different parts of the repository. All of these activities must be carried out with documented quality to satisfy the safety requirements. In other words, prognostication concerning the bedrock will proceed in parallel with the construction of the repository. This coordination can be tried and evaluated under realistic conditions within the framework of the Äspö Hard Rock Laboratory.

Studies of the radiological consequences in the biosphere if the barrier functions in the repository should for some reason not provide adequate safety are also being conducted at SKB. If releases should occur within something on the order of a few thousand years, for example due to early canister damage, the local ecosystem on the repository site is essential in determining the consequences of the nuclide dispersal. The Äspö Hard Rock Laboratory offers opportunities for conducting site-specific near-surface model studies where the activity distribution of different nuclides in ground and water is taken into account.

Against the background of the above motives, SKB has started the construction of the Äspö Hard Rock Laboratory. The laboratory provides an opportunity for research and development in a realistic and undisturbed rock environment down to the depth planned for the future deep repository. The Äspö Hard Rock Laboratory thus constitutes and important complement to the other work being conducted within SKB's research programme.

The standards of quality in the research are very high, and an overall ambition should be that the Äspö Hard Rock Laboratory should become an internationally leading centre for research and development regarding the construction of deep repositories for high-level waste in crystalline bedrock.

## 2.2 MAIN GOALS

The R&D activities in the Äspö Hard Rock Laboratory have the following main goals:

- **Test the quality and appropriateness of different methods for characterizing the bedrock with respect to conditions of importance for a deep repository.**
- **Refine and demonstrate methods for adapting a deep repository to the local properties of the rock in connection with design, planning and construction.**
- **Collect material and data of importance for the safety of the deep repository and for confidence in the quality of the safety assessments.**

The last goal is general for SKB's entire research programme.

## 2.3 STAGE GOALS

To meet the overall schedule for the siting programme, the following stage goals have been set up for the activities at the Äspö Hard Rock Laboratory.

Prior to the siting of a demonstration repository for spent nuclear fuel in the mid-1990s, the activities of the Äspö Hard Rock Laboratory shall serve to:

1 **Verify pre-investigation methods**
  - demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level, and

2 **Finalize detailed characterization methodology**
  - refine and verify the methods and the technology needed for characterization of the rock in the detailed site characterization.

As a basis for a good optimization of the deep repository system and for a safety assessment prior to the siting application, it is necessary to:

3 **Test models for groundwater flow and radionuclide migration**
  - refine and test on a large scale at repository depth methods and models for describing groundwater flow and radionuclide migration.

Prior to construction of the deep repository for demonstration deposition, which is planned to commence at the beginning of the next century, the following shall be done at planned repository depth and under representative conditions:

4 **Demonstrate construction and handling methods**
  - provide access to rock where methods and technology for guaranteeing high quality in the design, construction and operation of a deep repository can be refined and tested, and

5 **Test important parts of the repository system**
  - test, investigate and demonstrate on a full scale different components that are of importance for the long-term safety of a deep repository system.

These tests shall be able to be carried out with sufficient scope as regards time and scale to provide the necessary support material for regulatory approval of the start of construction. Certain tests may therefore have to be started in the mid-1990s.

## 2.4 COMMENTS ON THE GOALS

The main goals for the Äspö Hard Rock Laboratory are to refine and/or test three different kinds of skills prior to the construction of a deep repository:

- methods for characterizing rock,
- methods for adapting a repository to the local properties of the rock,
- methods for evaluating the safety performance of the rock.

The properties of the rock that are of importance in the different phases will vary. The testing of the quality of methods for rock characterization that is done at the Äspö Hard Rock Laboratory ties in at an early stage with the ability to interpret the flow and chemistry of the groundwater at possible repository depth on the basis of pre-investigations.

### Verify pre-investigation methods

*(Stage goal 1)*

Before detailed characterization starts on the candidate sites, the sites must be approved by various authorities. The supporting data on which this approval is based will be the results of the planned pre-investigations.

The programme for the pre-investigations is based on is based on, among other things, experience from the study site investigations, the Stripa project and the Äspö Hard Rock Laboratory. It is important to clarify the precision of the pre-investigations before making decisions on detailed characterization. This can be done in conjunction with the construction of the Äspö Hard Rock Laboratory.

Investigation of the rock is an iterative process, where assessment of the bedrock can proceed in a number of steps. Opinions can be given after geological map studies. Preliminary models of the bedrock can be set up and then refined in subsequent investigation steps. Such descriptions are set up step-by-step on different scales in the

Äspö Hard Rock Laboratory. A regional scale is applied to orient the site in a tectonic context and to describe the most important zones for groundwater flow and possible rock movements. The site scale, about 1 km, is relevant for laying out the repository in relation to existing fracture zones and for identifying suitable rock volumes for the location of shafts etc. A description on the hundred-metre scale is relevant for identifying volumes that are suitable for waste disposal. Rock descriptions on the ten-metre scale are used to describe the near field around the waste. The metre scale and smaller is important e.g. for studies of chemical interaction between the rock and the radionuclides, for study of the so-called disturbed zone around tunnels and for study of the equivalent water flow.

Pre-investigations from the surface and in boreholes can provide general descriptions as a basis for studying these questions. Detailed characterization, which is done in special investigation tunnels and shafts, can considerably deepen the level of understanding.

It is important to show for a rock volume that has been characterized from the surface, in boreholes and from tunnels and shafts that the judgements made on the basis of pre-investigations lead to the same principal conclusions as those later obtained after detailed characterization has been carried out.

The need to verify pre-investigation methods is primarily related to lend greater credibility to the data that will be available for making decisions are made on detailed characterization. The results of this work (verification of borehole investigation methods etc.) are, however, also of great importance for the subsequent construction of the deep repository. This will probably take place in stages, where the scope of each stage will be determined by local conditions and by the configuration of the deep repository that is finally chosen. Each construction stage is preceded by pre-investigations utilizing basically the same technology and methods as those used for pre-investigations from the ground surface. In the construction phase, it is thus of even greater importance that these methods have been thoroughly tested and verified.

### Finalize detailed characterization

*(Stage goal 2)*

The detailed characterization thus necessarily entails changes in the natural groundwater situation. It is therefore important to be convinced that essential data have been collected before the start of tunnel/shaft driving. The detailed characterization must be executed with rigour and thoroughness and with complete documentation to high standards. The pre-investigation and construction phases in the Äspö Hard Rock Laboratory provide excellent opportunities to develop and test the procedure for detailed characterization under realistic conditions. The Äspö Hard Rock Laboratory will demonstrate the deepening of knowledge that is possible to achieve in relation to the evaluations made during the pre-investigation phase.

### Test models for groundwater flow and radionuclide migration

*(Stage goal 3)*

In order for a siting application to be approved, it is important that the long-term safety of the repository can be demonstrated. This in turn requires demonstrating an understanding of the area's groundwater flow. This understanding is needed for emplacement of the waste, for determining the thickness of the engineered barriers, for assessment of different release scenarios and for the eventual sealing of the repository in the best manner. The Äspö Hard Rock Laboratory provides an opportunity for practical application of different theoretical models for how groundwater and substances dissolved in it are transported from the isolated waste, and how outward transport of radionuclides could take place.

### Demonstrate construction and handling methods

*(Stage goal 4)*

A deep repository consists of a large number of parts that are identical to each other. A KBS-3 repository, for example, consists of several thousand canisters, each of which is surrounded by highly compacted bentonite in a deposition hole. The different components (fuel, canister, clay, rock) combine to achieve a safe disposal. Other important components are e.g. sealing plugs for shafts, boreholes or tunnels, grouting shields for diversion of mobile groundwater and tunnel fill. All of these parts must be executed with a certain minimum quality in order for the repository in its entirety shall meet the safety requirements. When applying for a building permit, it is urgent to demonstrate that this minimum quality can be met. During pre-investigations and detailed characterization, a gradual increase in the level of detail of the description takes place. This description and understanding is deepened during the construction of the repository. It is important to demonstrate how data will be gathered and analyzed during the repository's construction phase. Before construction of the repository takes place, it is also possible to demonstrate different methods for making tunnels and deposition holes, for example drilling/blasting or full-face boring. The laboratory also provides a possibility for testing which measurements and analyses are to be made before choosing the rock volumes in which the waste is to be placed. It is also possible - for example in conjunction with full-scale tests – to develop and test methods for quality control and quality assurance in the execution of different parts of the deep repository system.

### Test important parts of the repository system

*(Stage goal 5)*

In a well-characterized rock mass, it is possible to carry out full-scale tests with parts of the selected repository concept. These tests may have to be commenced in the mid-90s and proceed for a long time. Tests can be performed on individual components in the repository system. The hydraulic interconnection between rock and buffer can be analyzed. The impact of e.g. temperature variations can be evaluated. Before a permit for sealing of the facility is issued, a demonstration can be made of how sealing of the plant is to be carried out. The results of these tests are submitted in support of the various permit applications. They are also expected to contribute towards increased confidence in and acceptance of the selected concept.

# 3 LICENSING OF THE ÄSPÖ HARD ROCK LABORATORY

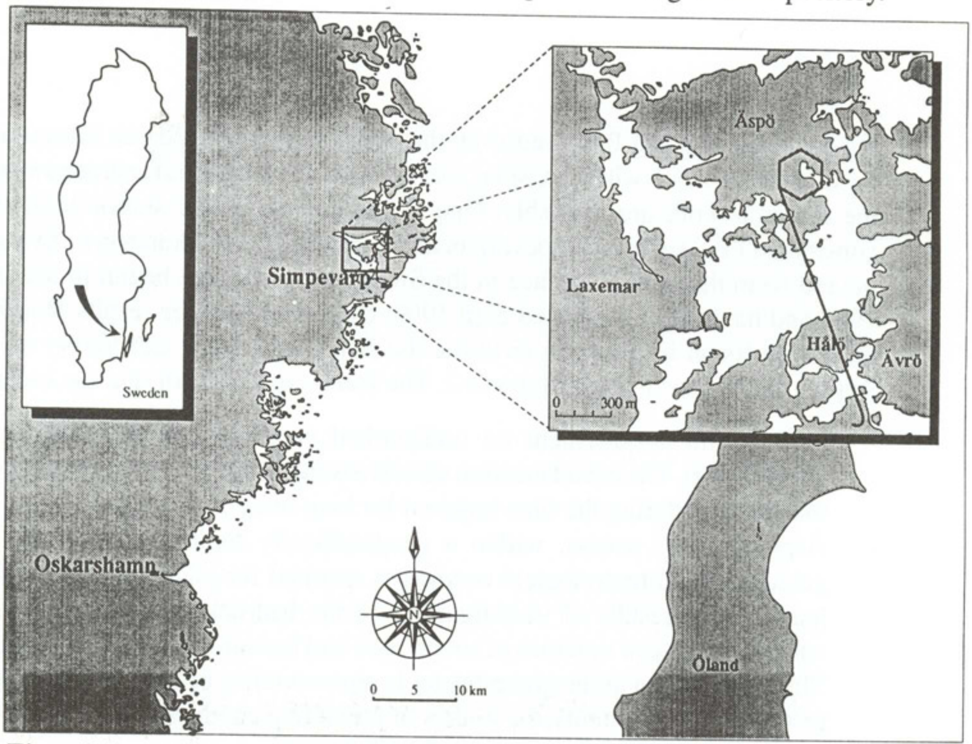
It was stated in R&D-Programme 86 that an underground research laboratory should be situated on a site where existing services and the kind of infrastructure needed for the research work are available. One of the nuclear power station sites should be considered first, such as Simpevarp in the municipality of Oskarshamn. Investigations on and from the ground surface in the Simpevarp area were begun in the autumn of 1986 and have since continued until 1990. On the basis of the results obtained, SKB made a decision in principle to locate the Äspö Hard Rock Laboratory on southern Äspö – see Figure 3-1 and Figure 3-2. The factors in favour of this site include:

- it meets the requirement on undisturbed conditions in the bedrock and the groundwater. The island location should ensure that other activities will not disturb the research during the time required for long-term experiments,
- Äspö provides access, within a geographically limited area, to the different geological and hydrological conditions required for planned tests and their evaluation. The results of investigations of the bedrock on Äspö show a suitable variation between volumes of sound rock and fracture zones of varying character. The composition of the groundwater is representative of Swedish coastal rock and provides an opportunity for studies of prevailing conditions and changes in these conditions resulting from the construction work,
- the nearness to the facilities at the Oskarshamn nuclear power station on the Simpevarp peninsula minimizes the need for surface buildings. Service facilities and personnel that can be utilized for the activities are available nearby. The various facilities at the Oskarshamn nuclear power station are also suitable for e.g. stationing of researchers, meetings etc.

In August 1989 the Government decided that the Äspö Hard Rock Laboratory should be reviewed under the Act on the Management of Natural Resources (NRL), and on 19 April 1990 a permit was obtained from the Government for establishing the facility on Äspö. The permit was subject to certain stipulations. For environmental reasons the tunnel entrance was moved from Äspö to the Simpevarp peninsula, which required construction of a 1.5 km long access ramp under Borholmsfjärden up to Äspö. A joint consultation group with representatives of the County Administration, the Municipality of Oskarshamn, the Oskarshamn Nuclear Power Station (OKG) and SKB was formed to deal with certain environmental questions. During the period 1990-1991, this group solved, for example, the problem of what to do with the rock waste from the excavation work. A building permit for the tunnel entrance and establishment on Simpevarp was obtained from the municipality in June 1990. Approval of a new detailed development plan under the Planning and Building Act (PBL) was required for the activities on Äspö (Äspö Research Village and the underground rock facility). The detailed development plan has been reviewed and approved by the Municipality, the County Administration and the Government, which gave its permission in October 1990.

The activities on Äspö are subject to the provisions of the Water Law, and a water rights ruling was handed down by the Water Rights Court in Växjö in September 1990. An important stipulation is that a monitoring programme for the groundwater table and water analysis shall be carried out. Private wells shall be monitored through 1995 and the project's own boreholes shall be monitored through 2004.

In conclusion, it can be mentioned that the actual site of the Äspö Hard Rock Laboratory is not being considered for the siting of the demonstration repository. If, however, suitable geological conditions are found nearby, this can be one of the candidate sites that is characterized in detail prior to siting of the repository.



***Figur 3-1.*** *Simpevarp area with environs*

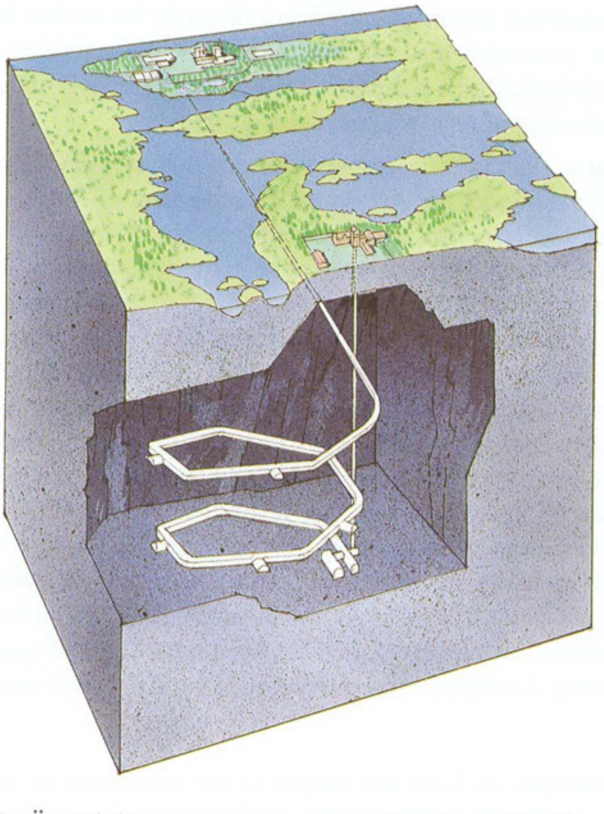


***Figure 3-2.*** *The Äspö laboratory's access ramp begins on the Simpevarp Peninsula. Via two spiral turns, the ramp reaches a depth of about 460 m.*

# 4 THE RESEARCH PROGRAMME FOR THE ÄSPÖ HARD ROCK LABORATORY

The programme for the Äspö Hard Rock Laboratory has been divided into three phases: a pre-investigation phase, a construction phase and an operating phase.

As with SKB's other research programmes, it is vital that the details of the programme emerge gradually as field data, results, models and experience become available. Figure 4-1 shows the current master schedule.

In the **pre-investigation phase**, the laboratory was sited. The natural conditions in the bedrock were analyzed and described. In parallel with the pre-investigations, the project's construction and operating phases were planned.

During the **construction phase**, 1990-1994, a number of investigations and experiments are being and will be conducted in parallel with the building activities.

The **operating phase** will begin in 1995. The present background report indicates the thrust of the investigations and tests that will be carried out during the operating phase. The final programme for the operating phase will be adjusted on the basis of the results from other projects and experience gained from the construction phase.

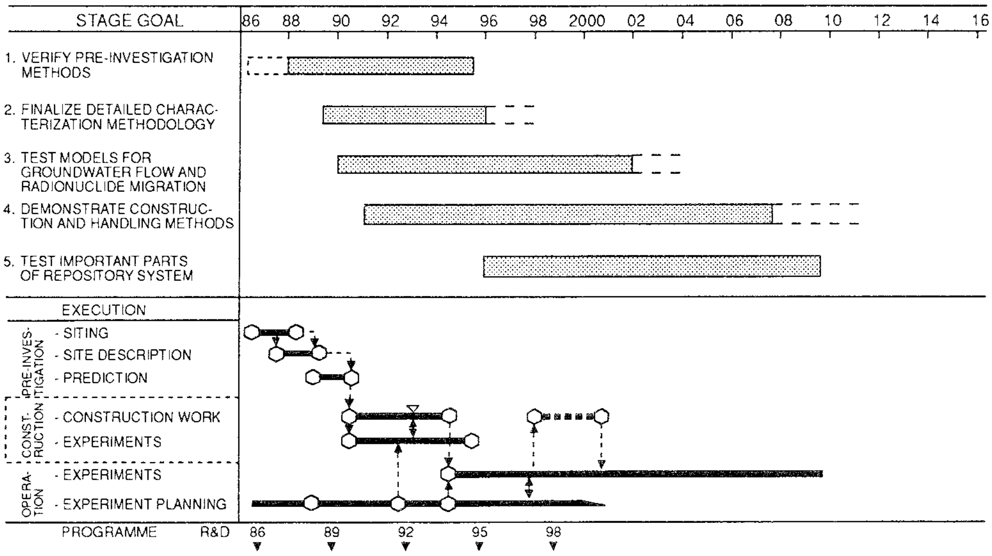


*Figure 4-1. Master timeschedule for pre-investigation, construction and operating phases, September 1992.*

# 5 RESULTS OF THE PRE-INVESTIGATION PHASE

## 5.1 PROGRAMME

The **pre-investigation programme** for the Äspö Hard Rock Laboratory was carried out during the period 1986 – 1990 with the following purposes, which were presented in R&D-Programme 86 and with a deepened description in R&D-Programme 89.

- Collect the geoscientific data required to determine whether it is possible to locate the underground research laboratory around Simpevarp and thereby meet the need for detailed characterization for validation.
- Collect the data required for the preliminary geometric layout of the underground research laboratory.
- Establish programmes for shaft sinking/tunnelling and measurements.
- Make a prediction of the geohydrological and geochemical changes that occur in conjunction with construction of the underground research laboratory.

The pre-investigation phase has been divided into the following three stages:

- the siting stage,
- the site description stage and
- the prediction stage.

## 5.2 EXECUTION

The pre-investigation phase has been conducted as a project with a project manager and principal investigators for geology, rock mechanics, geohydrology, water chemistry, instruments and field work.

The **siting stage** was begun with a regional survey comprising many different aerogeophysical methods (magnetometric, radiometric, slingram and VLF). On the islands of Ävrö, Äspö and in the Laxemar area, the aerogeophysical surveys were then complemented with gravimetric surveys and ground geophysical surveys in the form of magnetometry and VLF. Lineaments in the Simpevarp area were interpreted from different digital terrain models and the bedrock was mapped on a scale of 1:10000 around Simpevarp and on a scale of 1:50000 in a regional area. Fracture mapping and tectonic studies were carried out for the principal purpose of describing fracture geometries and characterizing the main tectonic zones in the region. Regional data from SGU's well records were analyzed. Geohydrological data from the construction of the nuclear power plants and CLAB were compiled. An inventory of the groundwater chemistry within Kalmar County was carried out with the aid of SGU's well records and then for shallow groundwater. A number of holes were percussion-drilled to obtain information on rock type and permeability in the shallow parts of the bedrock. Twelve percussion boreholes were drilled to begin with on Äspö, four holes on Ävrö and seven holes in the Laxemar area.

The **site description stage** has included drilling activities on Äspö, Ävrö and in the Laxemar area on several occasions. A preliminary geological, hydrogeological and hydrochemical model for Äspö was set up on the basis of three cored boreholes. A reference cored borehole was drilled in the Laxemar area. The bedrock on Äspö was mapped on a scale of 1:2000 and very detailed rock type determinations were made on outcrops along approx. 3 m wide cleaned trenches running all over the island. A detailed structural-geological analysis was performed with the aid of a newly-produced topographical map on a scale of 1:4000. An extensive fracture mapping programme was carried out on the outcrops along the cleaned trenches. Fracture data was analyzed with regard to strike, dip, density, length distribution and average spacing between fracture sets. The local tectonic picture was interpreted on the basis of magnetometric and geoelectric mapping of the entire island of Äspö, and ground radar measurements complemented the results on the southern part of the island. Hydrogeological investigations were carried out with the aid of long-term pumping tests (interference tests), spinner surveys, injection tests and air-lift tests in the boreholes, whereby the principal hydraulic conductors in the rock were identified. Boundary conditions in the hydrogeological modelling work were obtained via local hydrological studies. The hydrochemical conditions at depth were clarified by sampling and analysis from water-bearing sections in the boreholes KAS 02, 03, 04 on Äspö and from the borehole KLX 01 in the Laxemar area.

The main purpose of the **prediction stage** was to evaluate and compile all data for predictions of what is expected in the rock as the excavation progresses downward on Äspö. Based on the local investigations, southern Äspö was chosen as the most suitable siting for the laboratory. The investigations were also supplemented during this stage with percussion boreholes, cored boreholes to a depth of 500 m and pumping tests. Furthermore, extensive downhole geophysical measurements, rock stress measurements and seismic refraction measurements were performed. Since the tunnel entrance was moved to the Simpevarp peninsula, a nearly horizontal, over 700 m long cored investigation borehole (KBH 02) was drilled parallel to the access ramp. In all, twenty percussion boreholes and fourteen cored boreholes were drilled from the surface on Äspö, see Figure 5-1, during the pre-investigation phase.

The pre-investigation programme was concluded with a combined pumping and tracer test, where non-sorbing short-lived radioactive trace elements were used to

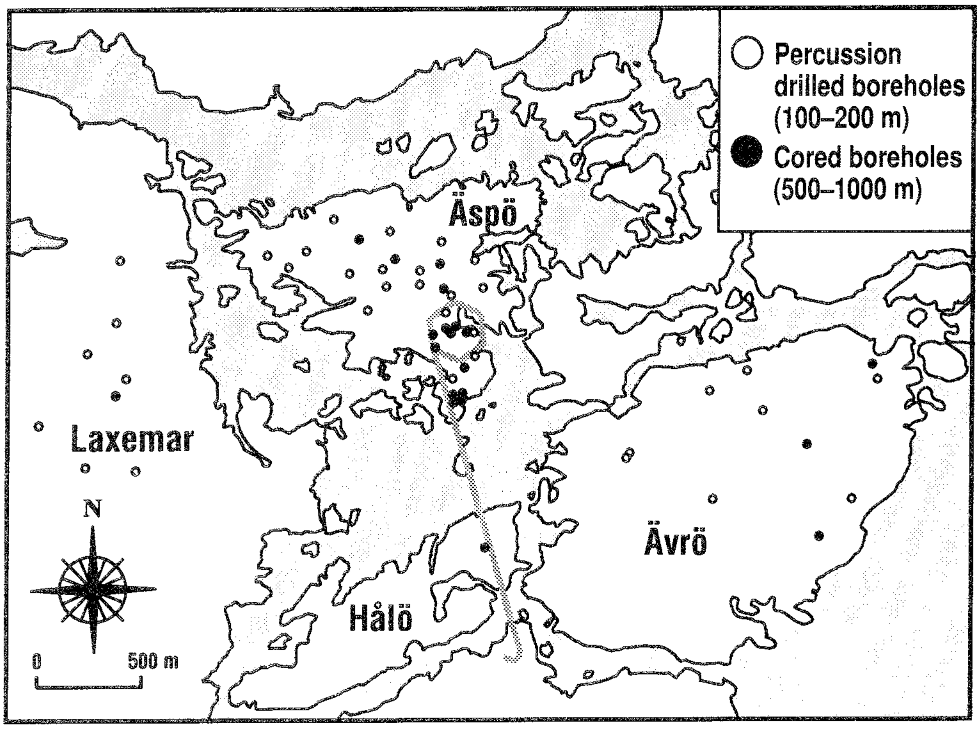


*Figure 5-1.* *The drilling programme on Äspö has been extensive. A total of 20 percussion boreholes and 14 cored boreholes have been drilled from the ground surface.*

study the connectivity between water-bearing zones and to obtain a measure of the flow porosity of the rock.

## 5.3 GENERAL PRE-INVESTIGATION RESULTS

The results from the **siting stage** have been reported in SKB Technical Report TR 88-16 /3/. To summarize, the regional-scale rock description shows that the Simpevarp area consists for the most part of granitic bedrock (Småland granite) with inclusions of basic rock types, greenstones. The information from the geological and geophysical surveys shows a tectonic picture of the Simpevarp area that is dominated by a nearly orthogonal system of fractures and fracture zones in the N-S and E-W direction. Aside from this system there are zones and fracture systems in a NW and NE direction that also form a nearly orthogonal system. There are probably also flat, subhorizontal structures.

Of importance for numerical models of the groundwater flow has been the fact that the Simpevarp area is surrounded by younger, granitic diapirs, which are also assumed to underlie the Simpevarp area at great depth. Regional well data show that these younger rock types are more permeable. It was judged that both Äspö and Laxemar were suitable sites for a laboratory.

The results from the **site description stage** have been reported in SKB Technical Report TR 89-16 /4/. A few important results are summarized below.

The further investigations for siting were directed above all towards Äspö. Äspö can be divided into three geological units: the northern block, the southern block and in between a broad shear zone with inclusions of mylonite. The zone, called the Äspö shear zone, is oriented ENE-NE. Judging from the cored borehole drilled on southern Äspö, Småland granite is the dominant rock type. Occasional crushed zones can be expected down to a depth of about 300 m, where the rock mass becomes a more quartz-poor variant of Småland granite, diorite, which appears to be more impervious than the overlying rock.

There are several zones of differing character on Äspö. The central shear zone has a northeasterly direction with an approximately $80^{o}$ northerly dip. NE 1 is judged to dip about $50\text{-}60^{o}$ towards the NW. Zone EW3 is east-westerly with a presumed dip of $85^{o}$ towards the south. Seismic reflection surveys have indicated possible subhorizontal zones at a depth of 300–500 m and 950–1150 m. They are characterized as rather short and unconnected. They could possibly be linked to the contact between granite and diorite, which also agrees with the results obtained from the transient cross-hole measurements. The water-bearing structures are coupled to what has been interpreted as high-conductivity zones and a more diffuse, pronounced system of persistent fractures with a north-northwesterly direction.

The groundwater chemistry samples have been taken in wells, percussion boreholes and cored boreholes. A matter of particular interest is the chloride content of the water. The chloride content of the saline groundwater varies from 3000 mg/l to 11000 mg/l. The chloride content of the surrounding Baltic Sea is 3000 mg/l. 7000 years ago the salt content was around 9000 mg/l. In the boreholes, the chloride content increases with increasing borehole depth, but the increase is non-linear. C-14 dating in the cored borehole KAS 02 puts the age of the saline water at 13000 years, while an age of 21000 years is indicated in KAS 03. The results cannot be translated directly to turnover time, since water samples are always mixtures, but the analyses indicate slow groundwater movements in the bedrock.

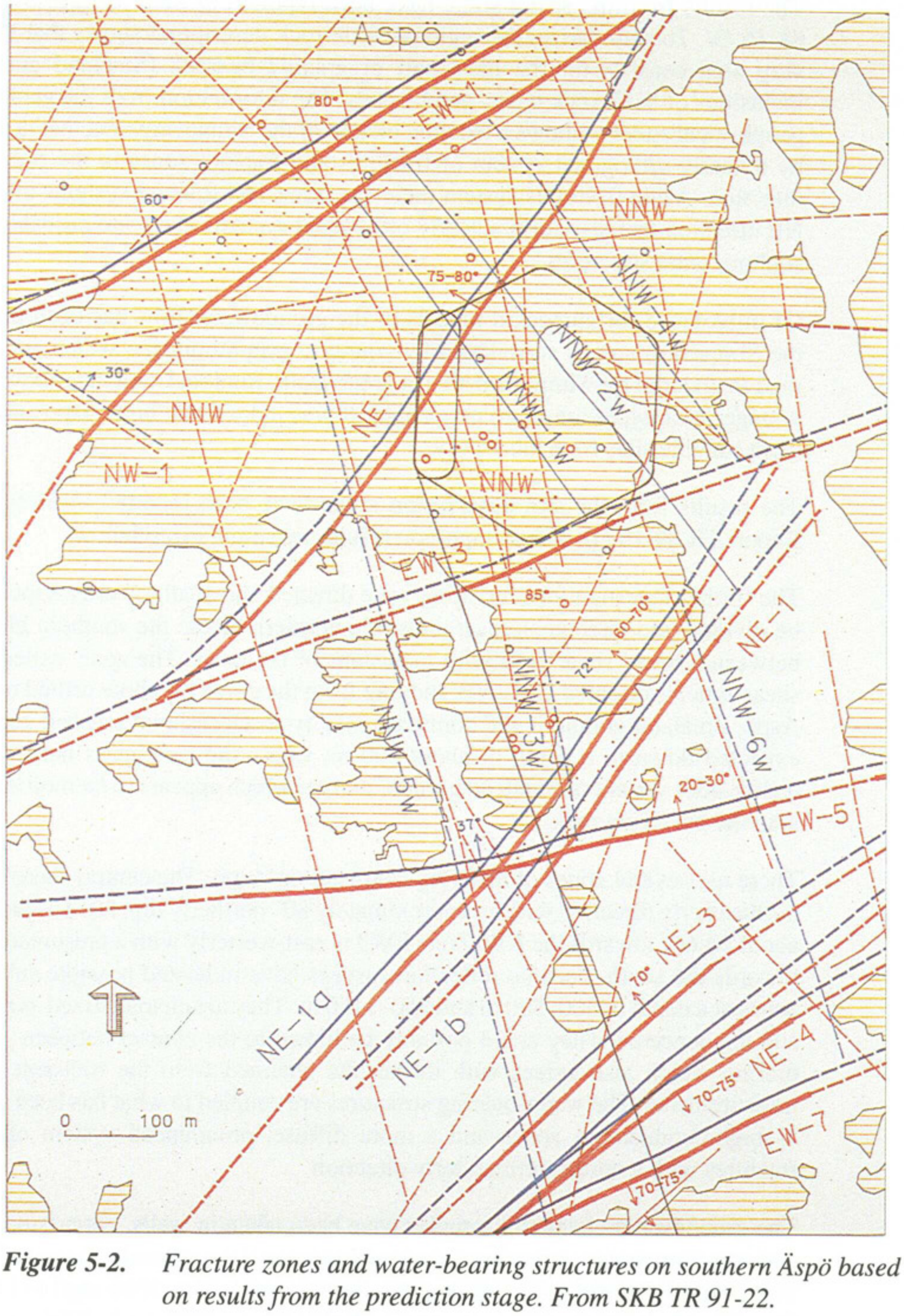


***Figure 5-2.*** *Fracture zones and water-bearing structures on southern Äspö based on results from the prediction stage. From SKB TR 91-22.*

In summary, southern Äspö was chosen for the siting of the Äspö Hard Rock Laboratory on the basis of the pre-investigations. Among the reasons for this siting, the following can be mentioned:

- There is a relatively homogeneous rock block with few well-defined groundwater-bearing structures on southern Äspö.
- Near to the above are a regional shear zone and areas with very homogeneous Småland granite.
- Areas beneath the surface of the sea are accessible immediately off Äspö, which give relatively well-defined hydraulic boundary conditions.

The pre-investigation phase was concluded with the **prediction stage**, see Figure 5-2. This stage has resulted in the publishing of four Technical Reports: 91-20, 21, 22 and 23 /5,6,7,8/. The first report summarizes all investigations made in the pre-investigation phase. The second report describes all the field methods and instruments that have been used. The third report deals with the evaluation of all investigations and how they led to integrated conceptual models of Äspö. The conceptual models cover the different subject areas and describe Äspö on different scales: the site scale (500 m), the block scale (50 m) and the detailed scale (5 m). The numerical groundwater flow model used to make predictions of the hydraulic effects of the Äspö Hard Rock Laboratory in the rock mass is also described in the evaluation report. The description takes up the choice of boundary conditions, parameters included and calibration efforts.

The fourth report is a systematic, subject-by-subject presentation of the predictions that are expected to be forthcoming as the laboratory is excavated down to a depth of 500 m. This prediction report has thus been prepared with the aid of the conceptual and numerical models and contains expected results on the different scales mentioned above.

## 5.4 RESULTS FROM THE PRE-INVESTIGATION PHASE IN RELATION TO THE STAGE GOALS

Some important results and development efforts during the pre-investigation phase are presented in this chapter, in relation to the stage goals set up for the Äspö Hard Rock Laboratory. Stage goals 1 and 3 are the main ones dealt with for this project phase, i.e. efforts aimed at verifying pre-investigation methods and testing models for groundwater flow and transport of solutes.

### 5.4.1 Results related to Stage goal 1 - Verify pre-investigation methods

**The process of validation**

During the pre-investigation phase, our understanding of the geological, rock mechanical, geohydrological, hydrochemical and geochemical conditions has been evaluated as integrated parts. The properties of the bedrock have been analyzed and described with models. The models have been both qualitative and quantitative and have been reported on different scales, see Figure 5-3.

On the basis of the pre-investigations, predictions were accordingly compiled of the bedrock at Äspö along the entire tunnel route. Validation, i.e. confirmation of the conceptual and numerical models set up, is defined according to the IAEA /9/ as "a process carried out by comparison of model predictions with independent field observations and experimental measurements. A model cannot be considered valida-

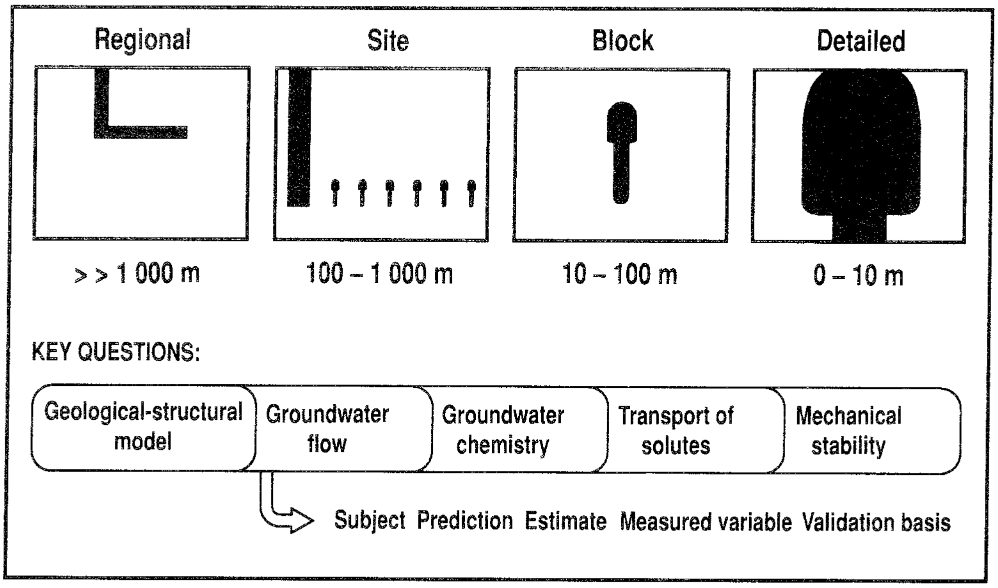


*Figure 5-3. Different subject disciplines and investigations are integrated in the Äspö Project. Analyses and modellings take place on different geometric scales.*

ted until sufficient testing has been performed to ensure an acceptable level of predictive accuracy."

The validation process for the Äspö Hard Rock Laboratory has been further refined within the project and by the project's Scientific Advisory Committee. Report PR 25-90-14 /10/ describes the process, which contains three essential elements:

- a systematic comparison of prediction and outcome,
- a careful scrutiny of the underlying structures and processes,
- a (subjective) judgement of whether the prediction is good enough.

Ultimately, the validation process is a tool for evaluating the accuracy of the pre-investigations and judging the capabilities and limitations of different investigation methods. This knowledge provides guidance in framing a balanced pre-investigation programme for the future candidate sites.

A separate prediction report, TR 91-23, has been compiled for the purpose of obtaining a systematic validation. In this report, the expected results for different geometric scales are presented by subject area. An example of a hydrogeological prediction on the site scale (500 m) for tunnel section 3064-3854 m is shown in Figure 5-4.

### Scale dependence in determination of hydraulic conductivity

The measured values of hydraulic conductivity in rock are approximately log-normally distributed. In recent years it has been noted for these distributions that mean values and variances are not identical on different scales.

The hydraulic measurements of conductivity on Äspö (the single-hole tests) have been made with different distances between the packers. This has made it possible to study how conductivity and its standard deviation vary with regard to rock type and measurement scale. The results show that the standard deviation decreases with increasing packer distance, i.e. that it is scale-dependent. The arithmetic means of conductivity decrease and the geometric means increase in relation to the test scale, see Figure 5-5.

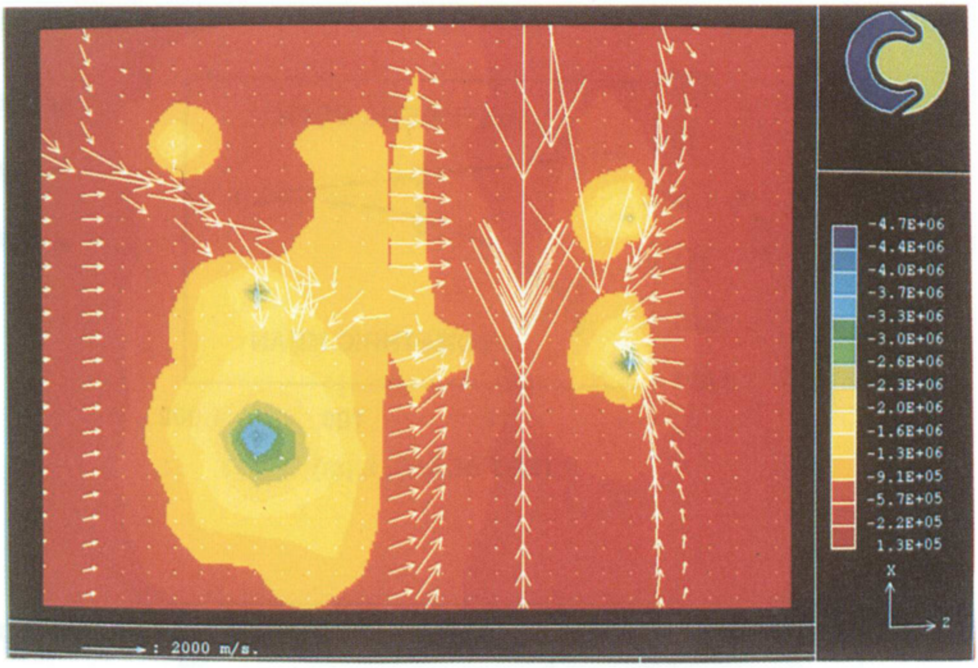


***Figure 5-4.*** *Examples of prediction of head and flow distribution in a vertical section through Äspö. Hydraulic head in Pa is shown numerically in the legend. The blue and green round markings represent the tunnel positions in the vertical section.*

### Investigation methods from the surface

As noted previously, a large number of geophysical and geological investigation methods from the ground surface have been employed during the pre-investigation phase, see TR 91-20. A few of the methods that were specially developed for and used within the Äspö project are presented below.

Lineament studies were carried out within the framework of the regional tectonic evaluation. The interpretations were made with the aid of the elevation database at the Swedish National Land Survey (Statens Lantmäteriverk, LMV). Elevation data are presented with a resolution of 50 m in an orthogonal grid system. The database was processed by the EBBA II image analysis system, and four different terrain models were developed: Hill shading, Residual elevation, Edge texture and Line texture. In these images, linear structures were then interpreted for Äspö with environs.

For the purpose of obtaining a very detailed picture of the geological bedrock conditions on the ground surface, the overburden was removed in approx. 1 km long and 3-5 m wide trenches on Äspö. The surface of the bedrock was then cleaned with compressed air and high-pressure water jets. In addition to geological mapping, extensive fracture mapping was also carried out. The fracture mapping has served as a basis for geohydrological modelling with discrete network methodology.

Geophysical digital data were processed by means of the GIS technique (Geographic Information System). This computer-based technique facilitates visualization and co-interpretation of different geophysical results and their information layers.

### Telescope-type drilling technique

To reduce the outflow of drilling fluid to the fracture system in the bedrock and thereby reduce the hydrochemical disturbance during the pre-investigations, a new drilling technique has been introduced in the Äspö project. This telescope-type drilling technique is a further development of conventional core drilling. The techni-

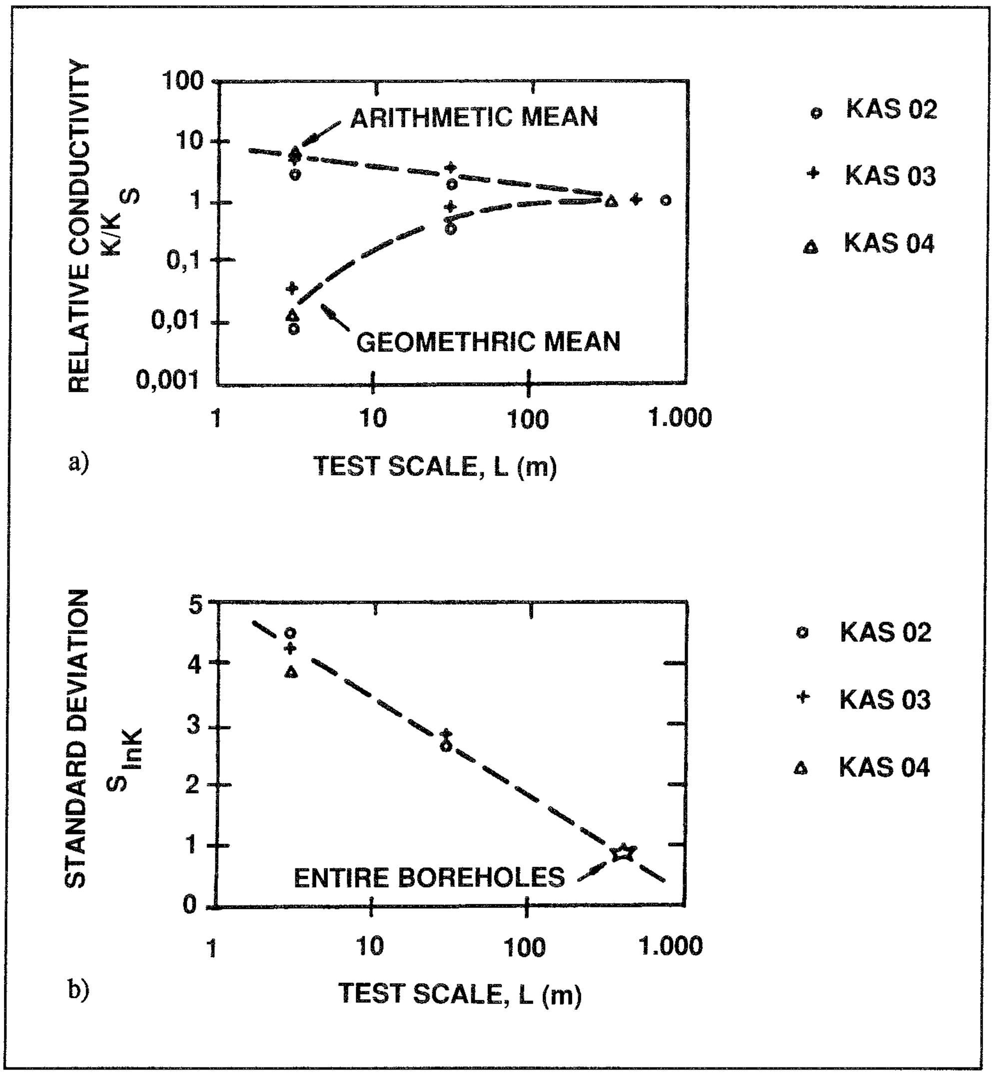


***Figure 5-5.*** *a) Relaitve hydraulic conductivities on different test scales.*
*b) Standard deviations for logarithmic conductivity distributions on different test scales.*

que also permits additional investigations and measurements in small-diameter boreholes, see Figure 5-6.

During core drilling at levels deeper than 100 m, a drawdown effect is created in the hole by means of compressed air. This prevents the outflow of drilling fluid to the geological formation. After the conclusion of drilling, the uppermost 100 m of the borehole has a diameter of 155 mm, while the rest of the hole has a diameter of 56 mm. The configuration of the hole then allows submersible pumps to be installed in the upper part. This facilitates test pumping and interference tests with water extraction from specified packer-sealed levels.

**Directional drilling**

To investigate the rock volume along the planned tunnel under Borholmsfjärden south of Äspö, a new drilling method was used which allows directional guidance of the drill bit. The borehole (KBH 02) was collared on Hålö, and after reaching the tunnel level the drilling was directed towards Äspö along the future tunnel route, see Figure 5-7.

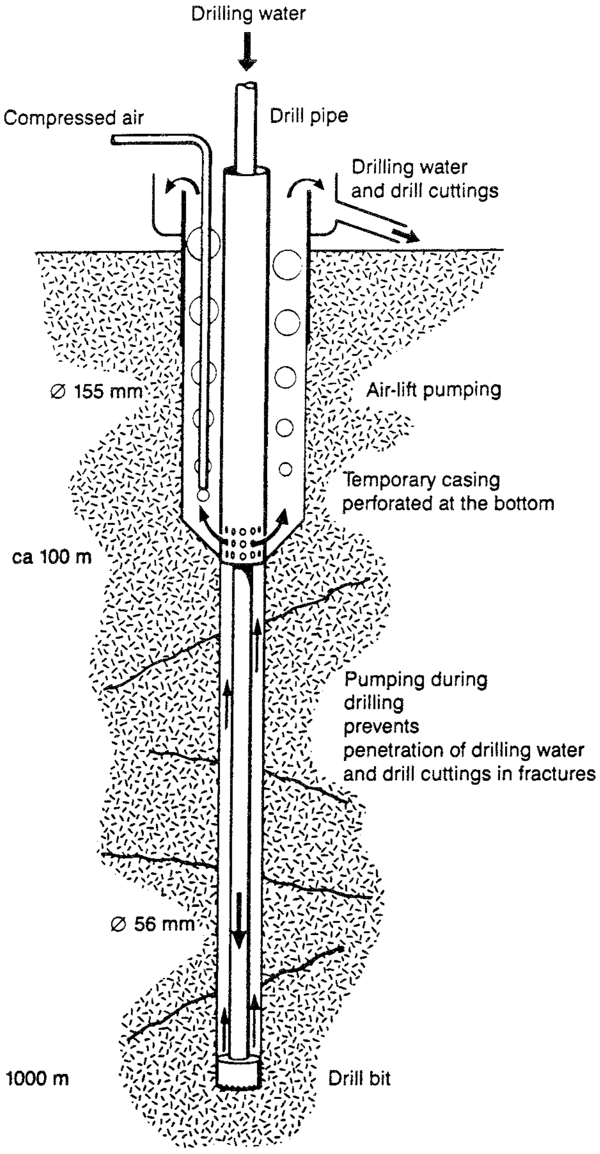


***Figure 5-6.*** *Principle of telescope-type drilling technique.*

## Borehole investigations

The investigation programme for the boreholes in the Äspö Hard Rock Laboratory's pre-investigation phase has been very comprehensive with core logging, petrophysical investigations, geophysical logging, rock stress measurements, geohydrological tests and groundwater chemistry analyses. Figures 5-8 and 5-9 show tables of the methods used in the cored boreholes and the percussion boreholes.

Besides the above-mentioned single-hole investigations, a number of tests aimed at measuring the mutual influence of different boreholes have been conducted. The methods employed for this include short-term test pumpings in the form of interference tests, long-term pumping tests and tracer tests.

A particularly valuable technique that was refined by SKB and employed in the Äspö Hard Rock Laboratory to trace water-bearing borehole sections has been flow-meter logging. The equipment, which measures the aggregate inflow along a borehole in

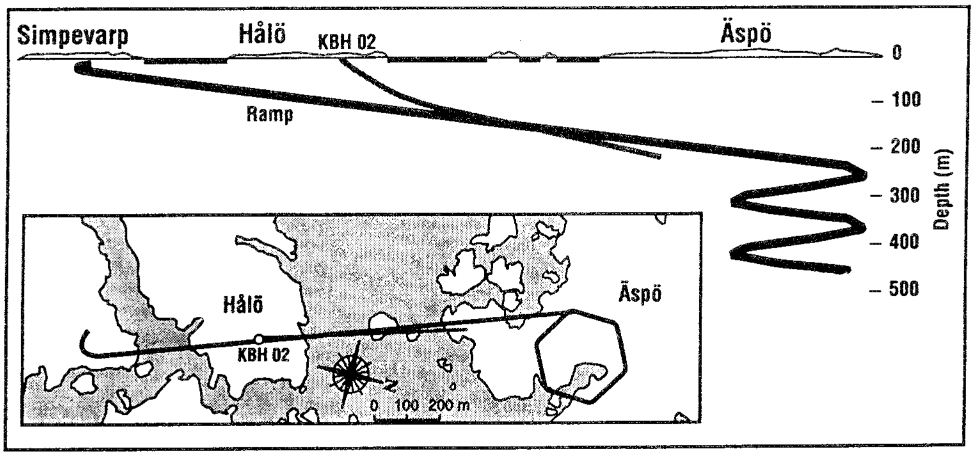


*Figure 5-7.* *Borehole KBH 02 was drilled to investigate the conditions along the access tunnel to Äspö.*

conjunction with pumping, maps the position of the water-bearing fractures with good accuracy. Two types of flow-meter probes have been used in the project. One measures the flow via a propeller. In the other, the magnitude of the water flow affects the travel time of an acoustic wave (the Doppler effect). The measurement principle is shown in Figure 5-10 and an example of measurement results is shown in Figure 5-11.

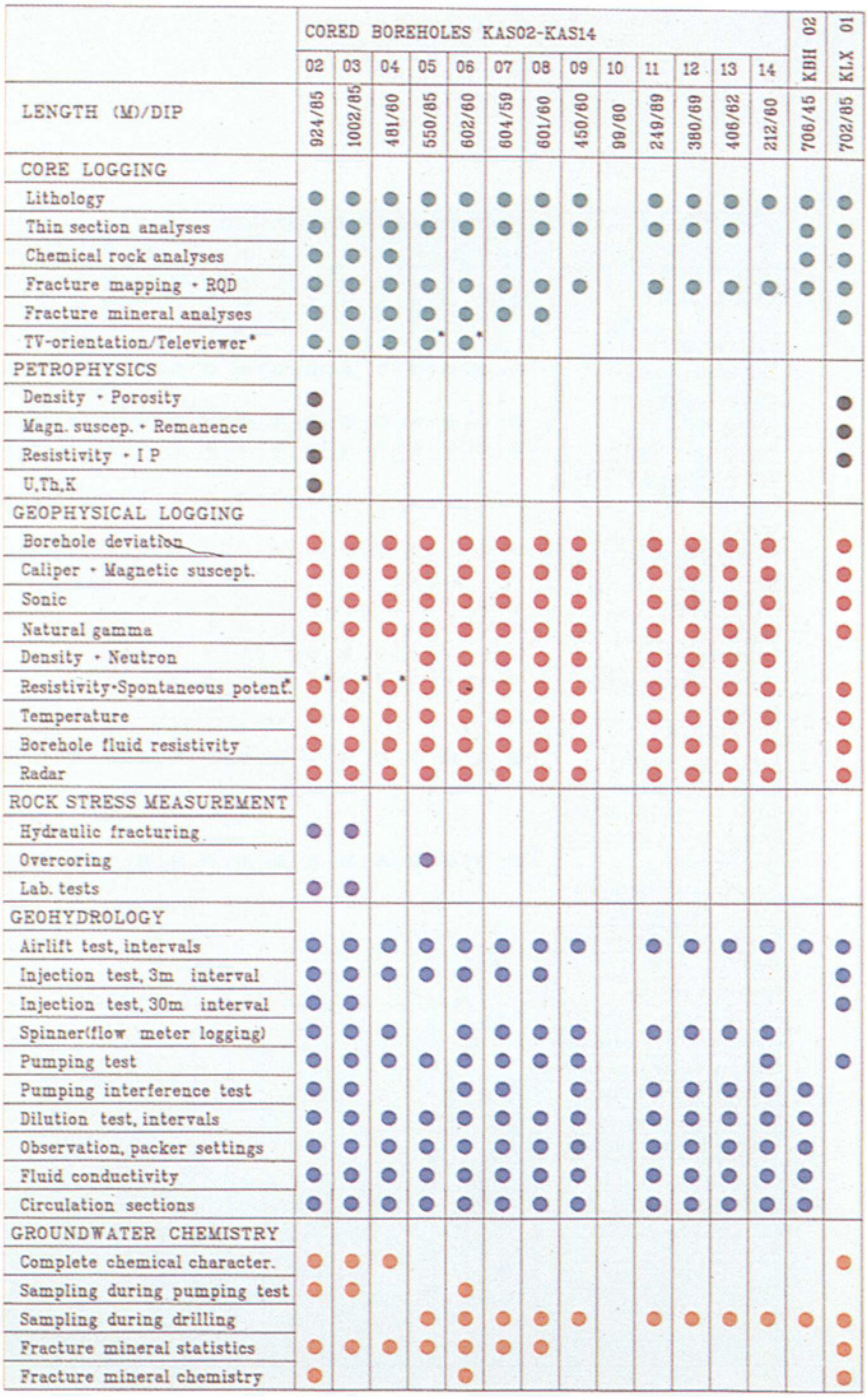
### Long-term monitoring of groundwater conditions

A measurement system for long-term monitoring of groundwater pressure and groundwater chemistry was installed during the pre-investigation phase. A multi-packer system has been developed by SKB and adapted to cored boreholes. The system, which is described in SKB TR 91-21, is designed so that it can perform groundwater level monitoring, water sampling, fluid conductivity recording and dilution measurement. In addition, tracer tests can be performed with the equipment, which is capable of making pressure measurements in up to nine sections in one and the same borehole.

## 5.4.2 Results related to Stage goal 3 – Test models for groundwater flow and radionuclide migration

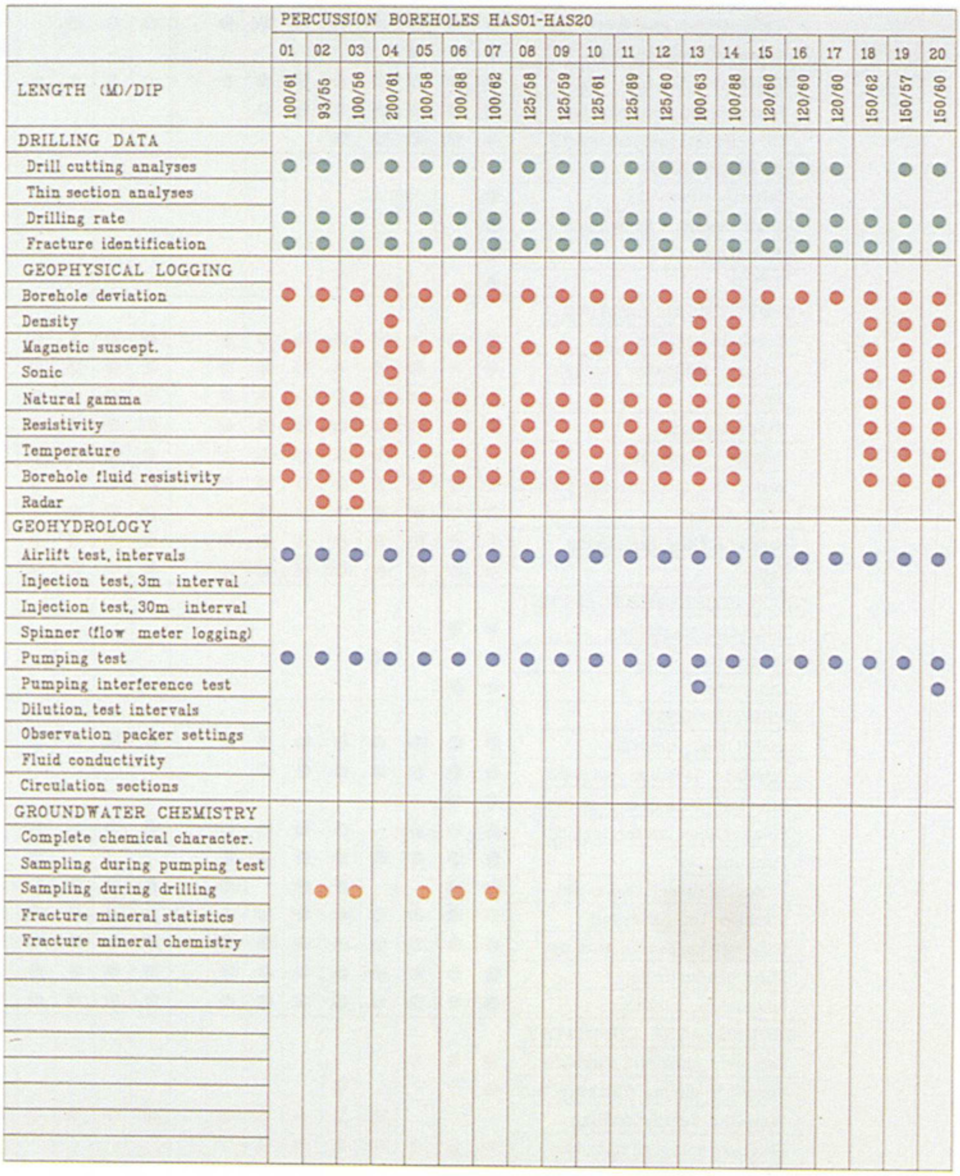
### Groundwater modelling

An essential purpose of the hydrogeological investigations is to test the capability of making predictions of the groundwater flow that will surround the repository and its canisters after the conclusion of deposition and plugging. Similarly, it is important to be able to foresee what flows will occur to the open tunnel systems during the construction of a deep repository. Different model concepts have been tested at the Äspö Hard Rock Laboratory. Owing to the heterogeneity of the rock and the different boundary conditions that are found at the facility, analytical solutions without numerical models cannot be employed. The main model code used to make predictions at Äspö is PHOENICS /11/.



| | CORED BOREHOLES KAS02-KAS14 | | | | | | | | | | | | | KBH 02 | KLX 01 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | | |
| LENGTH (M)/DIP | 924/85 | 1002/85 | 481/60 | 550/85 | 602/60 | 604/59 | 601/60 | 450/60 | 99/60 | 249/89 | 380/69 | 406/82 | 212/60 | 706/45 | 702/85 |
| CORE LOGGING | | | | | | | | | | | | | | | |
| Lithology | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● |
| Thin section analyses | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | | ● | ● |
| Chemical rock analyses | ● | ● | ● | | | | | | | | | | | ● | ● |
| Fracture mapping + RQD | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● |
| Fracture mineral analyses | ● | ● | ● | ● | ● | ● | ● | | | | | | | | ● |
| TV-orientation/Televiewer* | ● | ● | ● | ●* | ●* | | | | | | | | | | |
| PETROPHYSICS | | | | | | | | | | | | | | | |
| Density + Porosity | ● | | | | | | | | | | | | | | ● |
| Magn. suscep. + Remanence | ● | | | | | | | | | | | | | | ● |
| Resistivity + I P | ● | | | | | | | | | | | | | | ● |
| U,Th,K | ● | | | | | | | | | | | | | | |
| GEOPHYSICAL LOGGING | | | | | | | | | | | | | | | |
| Borehole deviation | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Caliper + Magnetic suscept. | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Sonic | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Natural gamma | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Density + Neutron | | | | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | |
| Resistivity+Spontaneous potent. | ●* | ●* | ●* | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Temperature | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Borehole fluid resistivity | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| Radar | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | ● |
| ROCK STRESS MEASUREMENT | | | | | | | | | | | | | | | |
| Hydraulic fracturing | ● | ● | | | | | | | | | | | | | |
| Overcoring | | | | ● | | | | | | | | | | | |
| Lab. tests | ● | ● | | | | | | | | | | | | | |
| GEOHYDROLOGY | | | | | | | | | | | | | | | |
| Airlift test, intervals | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● |
| Injection test, 3m interval | ● | ● | ● | ● | ● | ● | ● | | | | | | | | ● |
| Injection test, 30m interval | ● | ● | | | | | | | | | | | | | ● |
| Spinner(flow meter logging) | ● | ● | ● | | ● | ● | ● | ● | | ● | ● | ● | ● | | |
| Pumping test | ● | ● | ● | ● | ● | ● | ● | ● | | | | | ● | | ● |
| Pumping interference test | ● | ● | | | ● | ● | | ● | | ● | ● | ● | ● | ● | |
| Dilution test, intervals | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | |
| Observation, packer settings | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | |
| Fluid conductivity | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | |
| Circulation sections | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | |
| GROUNDWATER CHEMISTRY | | | | | | | | | | | | | | | |
| Complete chemical character. | ● | ● | ● | | | | | | | | | | | | ● |
| Sampling during pumping test | ● | ● | | | ● | | | | | | | | | | |
| Sampling during drilling | | | | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● |
| Fracture mineral statistics | ● | ● | ● | ● | ● | ● | ● | | | | | | | | ● |
| Fracture mineral chemistry | ● | | | | ● | | | | | | | | | | ● |

***Figure 5-8.*** *Investigations performed in cored boreholes. From SKB TR 91-20.*



| | PERCUSSION BOREHOLES HAS01-HAS20 | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| LENGTH (M)/DIP | 100/61 | 93/55 | 100/56 | 200/61 | 100/58 | 100/88 | 100/62 | 125/58 | 125/59 | 125/61 | 125/89 | 125/60 | 100/63 | 100/88 | 120/60 | 120/60 | 120/60 | 150/62 | 150/57 | 150/60 |
| DRILLING DATA | | | | | | | | | | | | | | | | | | | | |
| Drill cutting analyses | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● |
| Thin section analyses | | | | | | | | | | | | | | | | | | | | |
| Drilling rate | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Fracture identification | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| GEOPHYSICAL LOGGING | | | | | | | | | | | | | | | | | | | | |
| Borehole deviation | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Density | | | | ● | | | | | | | | | ● | ● | | | | ● | ● | ● |
| Magnetic suscept. | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | | ● | ● | ● |
| Sonic | | | | ● | | | | | | | | | ● | ● | | | | ● | ● | ● |
| Natural gamma | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | | ● | ● | ● |
| Resistivity | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | | ● | ● | ● |
| Temperature | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | | ● | ● | ● |
| Borehole fluid resistivity | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | | ● | ● | ● |
| Radar | | ● | ● | | | | | | | | | | | | | | | | | |
| GEOHYDROLOGY | | | | | | | | | | | | | | | | | | | | |
| Airlift test, intervals | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Injection test, 3m interval | | | | | | | | | | | | | | | | | | | | |
| Injection test, 30m interval | | | | | | | | | | | | | | | | | | | | |
| Spinner (flow meter logging) | | | | | | | | | | | | | | | | | | | | |
| Pumping test | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Pumping interference test | | | | | | | | | | | | | ● | | | | | | | ● |
| Dilution, test intervals | | | | | | | | | | | | | | | | | | | | |
| Observation packer settings | | | | | | | | | | | | | | | | | | | | |
| Fluid conductivity | | | | | | | | | | | | | | | | | | | | |
| Circulation sections | | | | | | | | | | | | | | | | | | | | |
| GROUNDWATER CHEMISTRY | | | | | | | | | | | | | | | | | | | | |
| Complete chemical character. | | | | | | | | | | | | | | | | | | | | |
| Sampling during pumping test | | | | | | | | | | | | | | | | | | | | |
| Sampling during drilling | | ● | ● | | ● | ● | ● | | | | | | | | | | | | | |
| Fracture mineral statistics | | | | | | | | | | | | | | | | | | | | |
| Fracture mineral chemistry | | | | | | | | | | | | | | | | | | | | |

**Figure 5-9.** *Investigations performed in percussion boreholes. From SKB TR 91-20.*

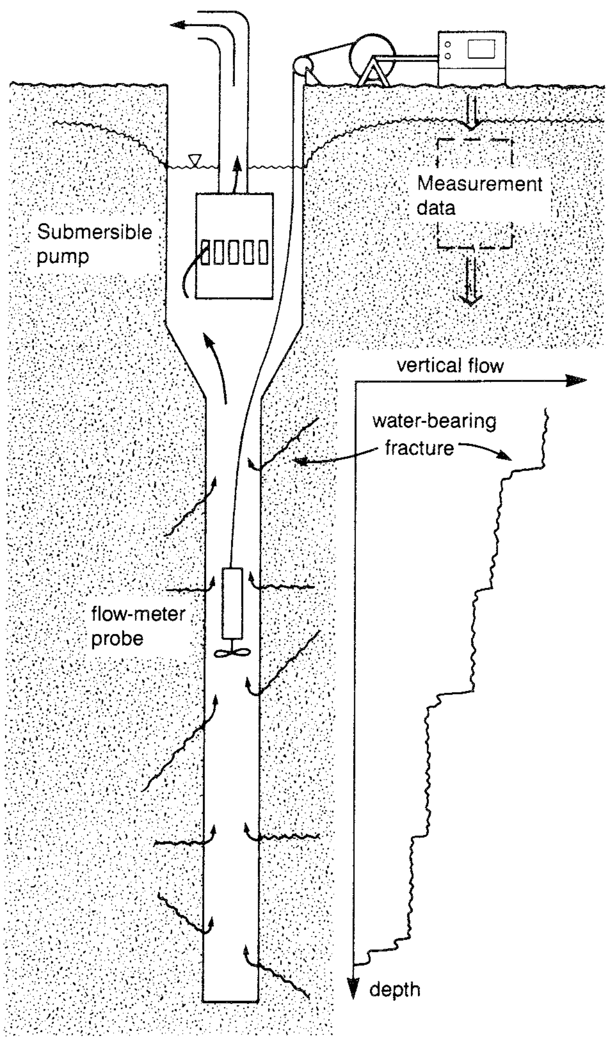


*Figure 5-10.* *The measurement priciple of flow-meter logging during pumping.*

The characterization and modelling of Äspö's complex water-bearing systems has followed two main lines. The major structures, such as conductive fracture zones, were identified and modelled deterministically. Geological, geophysical and hydrological methods were used to investigate the geometry of the zones and to assign hydraulic properties to the zones. The conceptual model and equivalent numerical model were then calibrated against interference tests, surrounding groundwater pressure and salinity for the water. The rock in between the zones was treated as a stochastic continuum. Long-normal distribution was assumed and the median value and standard deviation were adjusted ("scaled") with respect to cell size in the model.

The number of cells in the three-dimensional model of Äspö amounts to about 100 000. This entails a cell size of 20 m in the rock volume at the laboratory itself. At the tunnel wall, the cell size is 2 m.

In the horizontal plane the model covers an area of 1920 x 1500 m with a vertical depth of 1290 m.

The infiltration capacity at the ground surface, the upper boundary, has been estimated to be 3 mm/y through model calibration. The coastal wetlands are assumed in the model to have levels equal to that of the Baltic Sea. No flow takes place through the

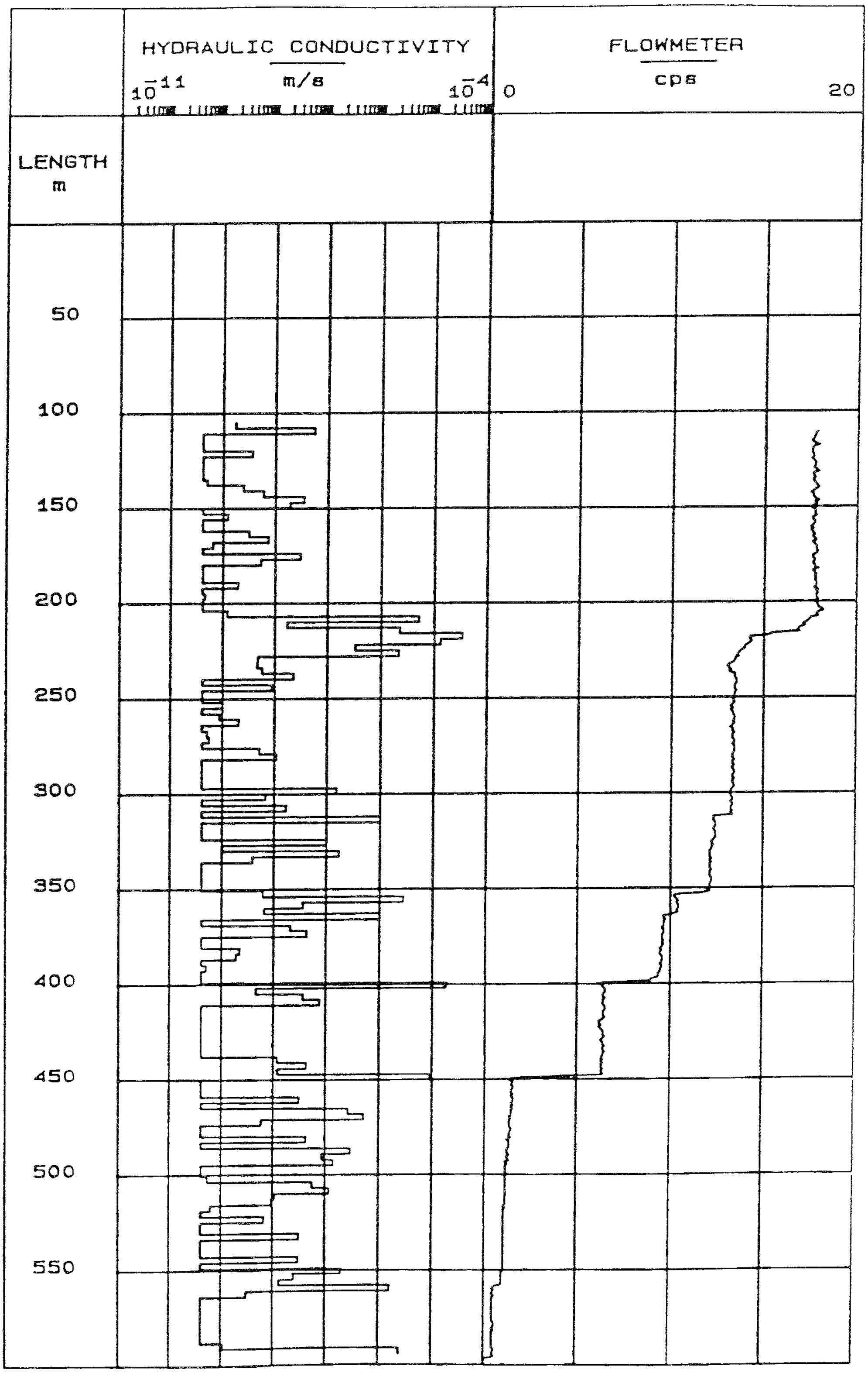


*Figure 5-11.* *Example of measurement results from flow-meter logging in borehole KAS 06. The cumulative inflow value from flow-meter logging is shown together with the hydraulic conductiviiities from 3 m test sections.*

lower model boundary. The pressure along the model sides is hydrostatic. The salinity is 0.7% at sea level, increasing linearly with depth along the sides of the model to 1.8% at the lower boundary of the model.

The PHOENICS code has been used to calibrate the model against the hydraulic tests and to make predictions of how the surrounding groundwater situation will change due to the blasting of the laboratory's tunnel system. The inflow to and the pressure around the tunnel have been calculated, as has the salinity of the inflowing water, see Figure 5-12.

**Tracer test, LPT 2, with modelling**

At the end of the pre-investigation phase, a large-scale tracer test was conducted in conjunction with a long-term pumping test, LPT 2, in borehole KAS 06. Uranine and three short-lived radioactive isotopes (In-114, I-131, Re-186) were injected into fracture systems in boreholes around the sampling borehole. Three of the tracers – from KAS12, KAS08 and KAS05 – could later be detected. The experiment was combined with a large number of dilution measurements in order to determine the groundwater flow in borehole sections.

Numerical simulations, without allowance for dispersion, had been conducted prior to the experiment with the above-described model. For flow porosities on the order of $5 \times 10^{-4} - 1 \times 10^{-3}$, the model shows good agreement with reality as far as the travel times of the tracers are concerned. Besides the travel times, pressure responses to pumping were modelled. The drawdowns also show good agreement between the model and the pumping test. The final report on the test will be published in the autumn of 1992.

This type of investigation is essential for the development of general model structures in the future. Based on the experiment, valuable information has been obtained on the fracture zones on Äspö.

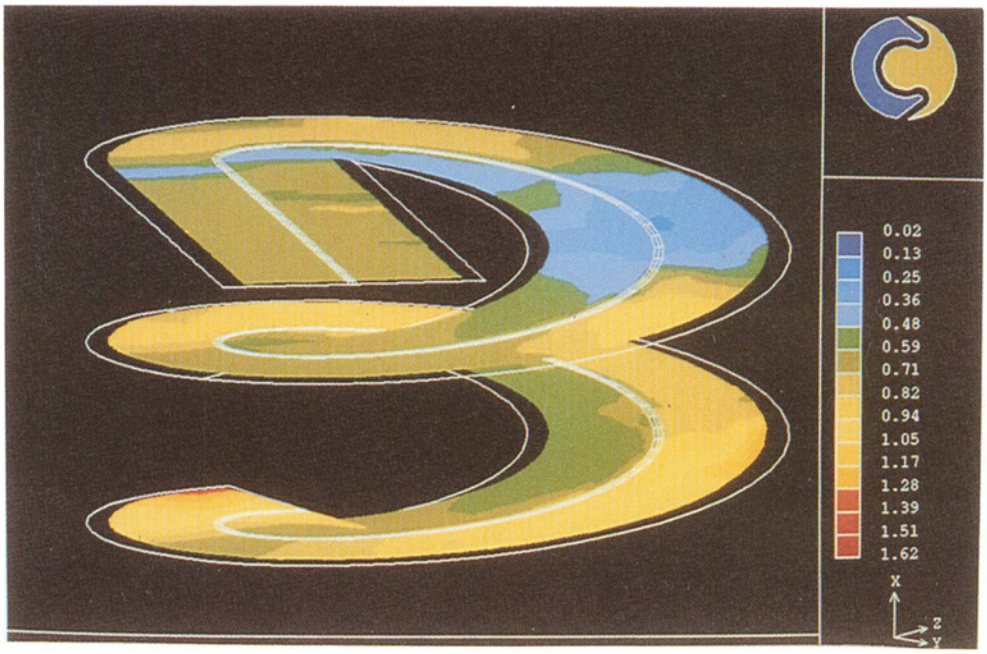


***Figure 5-12.*** *Estimated salinity of groundwater seeping into the tunnel after blasting to full depth (steady-state phase).*

# 6 CONSTRUCTION PHASE - PROGRAMME AND RESULTS

The construction work for the Äspö Hard Rock Laboratory commenced on 1 October 1990. The 3400 m long access ramp with a cross-sectional area of about 25 m2 is being blasted to a depth of about 460 m. In September 1992, the excavation work had reached nearly the 1600 m mark to a depth of just over 200 m below the surface.

## 6.1 TECHNICAL PROGRAMME FOR 1992-1994

### 6.1.1 General

The programme for the current construction phase was presented in outline form in R&D-Programme 89.

Since the properties of the bedrock nearest the deposition site and the deposition tunnels are of the greatest importance for the safety of a deep repository, it is essential that the degree of detail in the investigations during the construction phase be gradually increased. The investigations on the future experimental levels will therefore be more detailed than at the beginning of the tunnelling. The investigations during the tunnelling are therefore divided into two stages as defined below:

*Stage 1* Excavation of the access tunnel to a depth of about 330 metres, corresponding to a tunnel length of about 2500 m.

This data quantity is deemed to be sufficient for testing much of the conceptual model for Äspö, see SKB TR 91-22, and the corresponding predictions in SKB TR 91-23. It is also deemed to be adequate for making the evaluation of investigation methods to be used in the siting programme.

The excavation of elevator and ventilation shafts to the ground surface should also be completed during this phase.

*Stage 2* Excavation of the tunnel down to a depth of about 460 m, corresponding to a total tunnel length of more than 3400 m.

During the tunnelling from about 330 m down to about 460 m, the base documentation of the bedrock will be performed as before, but in part with a different purpose. The construction of the Äspö Hard Rock Laboratory at these levels will primarily be utilized to test methodology for **progressive characterization and progressive design.**

The "design-as-you-go" philosophy has a long tradition within underground construction. This tradition involves a) investigation of the rock b) design c) excavation and documentation d) evaluation with corrective measures regarding investigation, design and documentation.

After completed tunnelling, a "final" conceptual model of the bedrock on Äspö will be presented. It will be compared with the models set up during the pre-investigations on Äspö, see SKB TR 91-22.

The construction phase also includes some blasting-out of areas for some of the experiments to be conducted during the operating phase as well as continued driving of elevator and ventilation shafts down to a level of about 460 metres.

If later investigations within the framework of the general research programme should show that the repository should be located deeper than about 500 m, further excavation to greater depth, up to 700 m, may be undertaken.

In the SKB R&D-Programme 89, a pause in the tunnelling of about 6 months was planned between stage 1 and stage 2.

However, the ongoing work is being carried out more flexibly than originally planned. Instead of one big report/evaluation, several smaller ones are being done instead.

SKB's desire to refine and demonstrate methods for design-as-you-go means that the work of investigation must be done more hand-in-hand with the work of design/planning. Design-as-you-go requires a more flexible reporting of results than the reporting of the predictions from the pre-investigation phase. Some of the data collection and methodology evaluation that had been planned to be done during the pause between stage 1 and stage 2 is being scheduled earlier.

The pause between stage 1 and stage 2 can thereby be omitted.

### 6.1.2 Programme for construction phase 1992–1994

The RD&D activities in the construction phase are being carried out to be able to fulfil stage goals 1, 2 and 3 of the Äspö project. A number of sub-projects for the years 1992–1994 are presented below in relation to these stage goals.

**Stage goal 1 – Verify pre-investigation methods**

**Validation of conceptual models** – The present-day structure of data collection – comparison with prediction – evaluation – scrutiny in the Scientific Advisory Committee will be retained. Based on the results and experience gained during the construction phase, it is deemed to be possible to complete the validation work with the data obtained to a depth of about 330 m. Based on supplementary documentation in the tunnel section to the 460 m level, "final" conceptual models will be presented for the bedrock on Äspö.

**Evaluation of pre-investigation methods** – A large number of investigation methods and instruments have been used in the pre-investigation phase on Äspö. The appropriateness and reliability of the methods shall be evaluated prior to the siting of the demonstration repository. SKB shares the opinions presented during the course of the work by SKN and SKI that method evaluation is an essential task for the project. Method evaluation should answer questions regarding, among other things, the resolution, interpretability, appropriateness and usefulness of methods.

**Stage goal 2 – Finalize detailed characterization methodology**

**Documentation and data collection** – The documentation group stationed at the site office will continue its work with documentation and data collection regarding, among other subjects, geology, rock mechanics, geohydrology and water chemistry.

**Passage of fracture zones** – In conjunction with the ongoing tunnelling work, tests have already been conducted of a methodology for pinpointing fracture zones, for characterizing the zone in connection with zone passage and for conducting controlled grouting. The results of this work will be reported during 1993. The report material will include recommendations for supplementary development of construction technology, in particular grouting technology.

**Rock volume description - Siting of the facility** – The crystalline rock is a heterogeneous material. Some parts are severely crushed. The philosophy for repository construction is to modify the geometric configuration of the repository as the work progresses so that poor-quality volumes of rock are avoided.

Southern Äspö is delimited by several major fracture zones. There is a risk that the major fracture zone NE-1 south of Äspö will intersect the facility. In view of technical construction-related difficulties etc., this zone should be avoided. Supplementary investigations will be commenced in the autumn of 1992 to pinpoint this zone more precisely. On the basis of the investigation results, the tunnel between 330 and 460 m will be routed through the better (for construction purposes) rock. The investigations are primarily being focused on geological and rock-mechanical conditions. The work is supported with visual aids (CAD). Completion of the investigation and construction work will be followed by evaluation and framing of recommendations.

**Rock volume description - Siting of experimental areas** – The experiments that are to be carried out during the operating phase will be preliminarily sited during 1993. Supplementary investigations will be conducted during the construction period to finally site the experiments. The investigations of the rock volume for the experiments are being conducted with the philosophy that has been used to verify the pre-investigations.

**Rock volume description - Siting of suitable near field for canisters** – Fixed criteria for the emplacement of canisters do not currently exist. However, some general guidelines can be presented. A suitable rock environment is that the near field is mechanically stable, that the chemical environment is reducing, and that the water flux is low.

Pre-investigations for a repository aim at determining a suitable site for a repository area. The subsequent detailed characterization is supposed to confirm that a suitable repository volume is available. Unsuitable canister positions will gradually be rejected during the construction of the repository. A methodology for this will be tested at the Äspö Hard Rock Laboratory.

An initial phase includes estimating the number of canister positions in a given rock volume on Äspö that meet requirements on mechanical stability, chemically reducing environment and low water flux. The low water flux is safety-enhancing, but is also good from a practical viewpoint.

**Analysis of constructability** – Experience from design/planning and execution of the facility will be compiled and reported. A methodology for "constructability" analysis will be tested. Investigation data will be used in a systematic fashion to describe how the construction work is to be planned and executed technically. The analysis will also lead to systematic assessments of the amount of labour (rock support work) and time required.

### Stage goal 3 - Test models for groundwater flow and radionuclide migration

**International Task Force for modelling** – In parallel with the construction phase, a Task Force with participants from the Äspö project's international representatives will commence modelling with different calculation codes.

**Redox test** – A redox experiment was initiated in 1991 in a side tunnel at the 510 m section in the access tunnel. The purpose of the experiment is to determine the redox kinetics when oxygen-rich water penetrates through the bedrock's fracture systems, which are originally reducing. The test will continue during the rest of the construction phase and in part during the operating phase.

## 6.2 RESULTS FROM THE CONSTRUCTION PHASE IN RELATION TO THE STAGE GOALS

Some important results and development work during the construction phase are presented here in relation to the stage goals set up for the Äspö Hard Rock Laboratory. This project phase mainly concerns stage goals 1, 2 and 4.

### 6.2.1 Results with respect to Stage goal 1 – Verify pre-investigation methods

**Validation of geology in part of access tunnel**

The outcome of the predictions is evaluated in stages. The predictions in the tunnel apply to the section starting from 700 m. A preliminary prediction was, however, carried out for the 0–700 m section .

Prediction versus outcome has been reported in PR 25-92-02 /12/ and commented on in PR 25-92-06 /13/. For this tunnel section under Borholmsfjärden, it was only possible to make geological predictions on the basis of the pre-investigations. In the judgement of the Scientific Advisory Committee, the outcome in terms of rock type distribution and fracture pattern exhibits good agreement between surface mappings and tunnel observations, see Figure 6-1 and 6-2.

### 6.2.2 Results with respect to Stage goal 2 – Finalize detailed characterization methodology

**Documentation and data collection**

One of the most important duties of the site office is to take care of documentation and data collection. Data collection mainly takes place through:

- monitoring of groundwater pressure and salinity in some 140 points in surrounding boreholes,
- daily documentation in the tunnel in connection with each blasting round,
- investigation holes every 20 m along the tunnel,
- special investigations to answer specific questions.

A separate manual, PR 25-91-10 /14/, that defines data collection has been written for the construction phase. A documentation group takes care of data collection after each blasting round. Overviews are presented subject-by-subject for each 150 m of tunnel advance. Figure 6-3 shows an example of rock mechanics information. Similar presentations are made regularly for geohydrological, water chemistry and geological observations as well, see Figures 6-4 and 6-5.

Monitoring of groundwater pressures and flows takes place on-line with the aid of an automated central data collection system for the Äspö Hard Rock Laboratory (HMS, Hydro Monitoring System). The measurement points are situated at different levels in boreholes on Äspö and along the tunnel. Drawdown effects caused by tunnelling can thereby be ascertained immediately. Similarly, long-term trends in the hydrological cycle at Äspö are followed. Figure 6-6 shows a schematic illustration of the monitoring system.

**Feedback investigation-construction**

The rock work for the Äspö Hard Rock Laboratory is done using a normal drilling/blasting procedure. The routines that have been developed for coordination between construction and investigations are working well. There is also constant feedback during the course of the excavation work between the investigation results and the excavation methods (design-as-you-go). Geodata obtained from the running

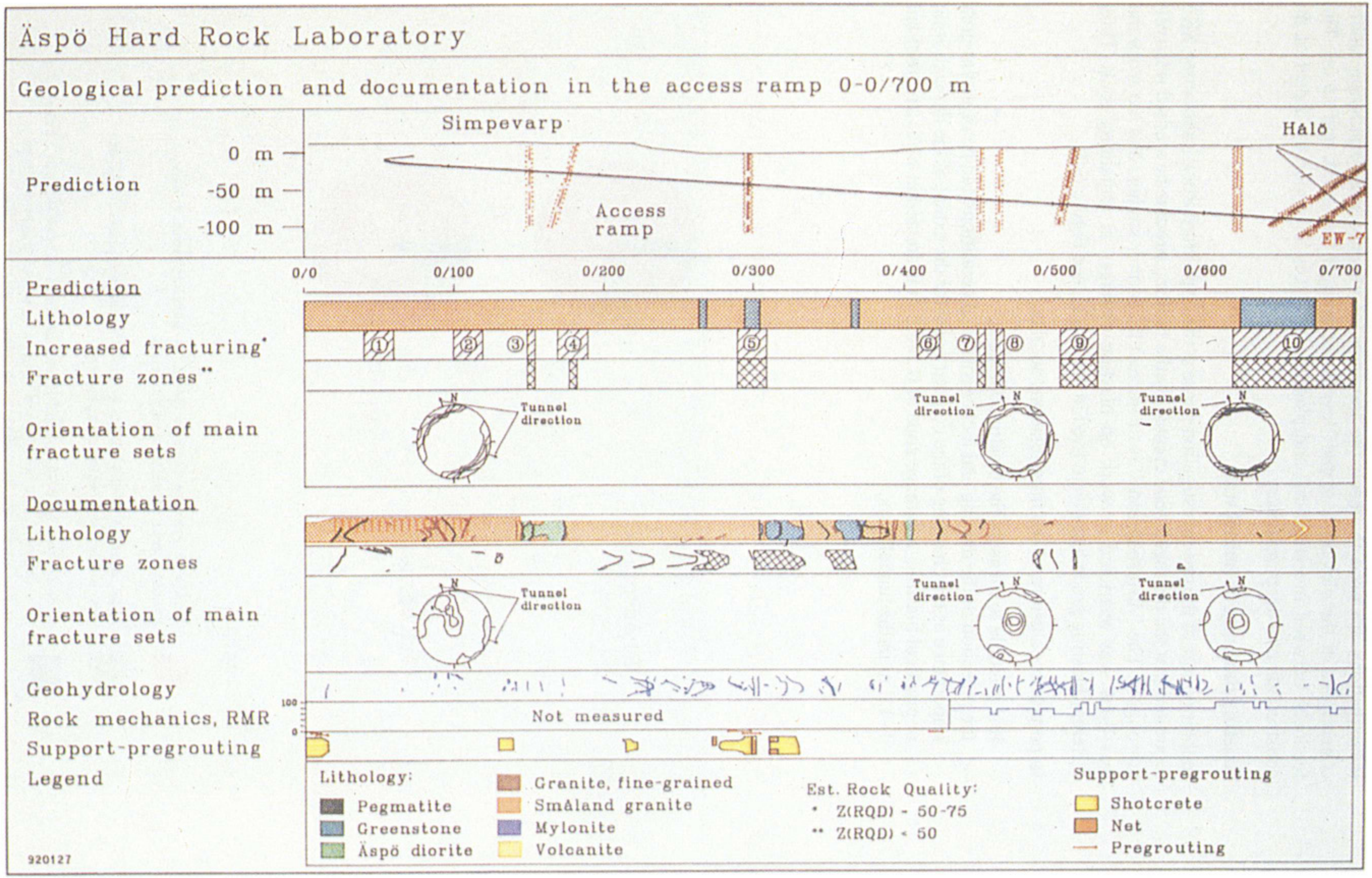


*Figure 6-1. Geological predictions and tunnel documentation, section 0–700 m in the access tunnel.*

investigations are used to check the locations of elevator and ventilation shafts, connections at the elevator's stopoff levels, location of the spiral, and so on. This feedback between investigations and planning/design is an important aspect of the construction of a deep repository.

**Blasting damages at tunnel wall**

In their review of the pre-investigation phase at the Äspö Hard Rock Laboratory, SKN requested that the damaged zone created by the blasting process be studied relatively thoroughly. The "disturbed zone" is of interest for further studies, and the work that was done was restricted to work on blasting damages in remaining rock. Three different blasting procedures were tried in the tunnel, see Figure 6-7.

Important conclusions of the investigations are that

- it is possible to measure the blasting damages,
- the precision of the drilling and local geological conditions can be of just as great importance as the charging of the contour holes for the extent of the damage zone,
- in practical blasting, a damage zone of 0.3–0.5 m is created in walls and roof and 1–1.5 m in the tunnel floor.

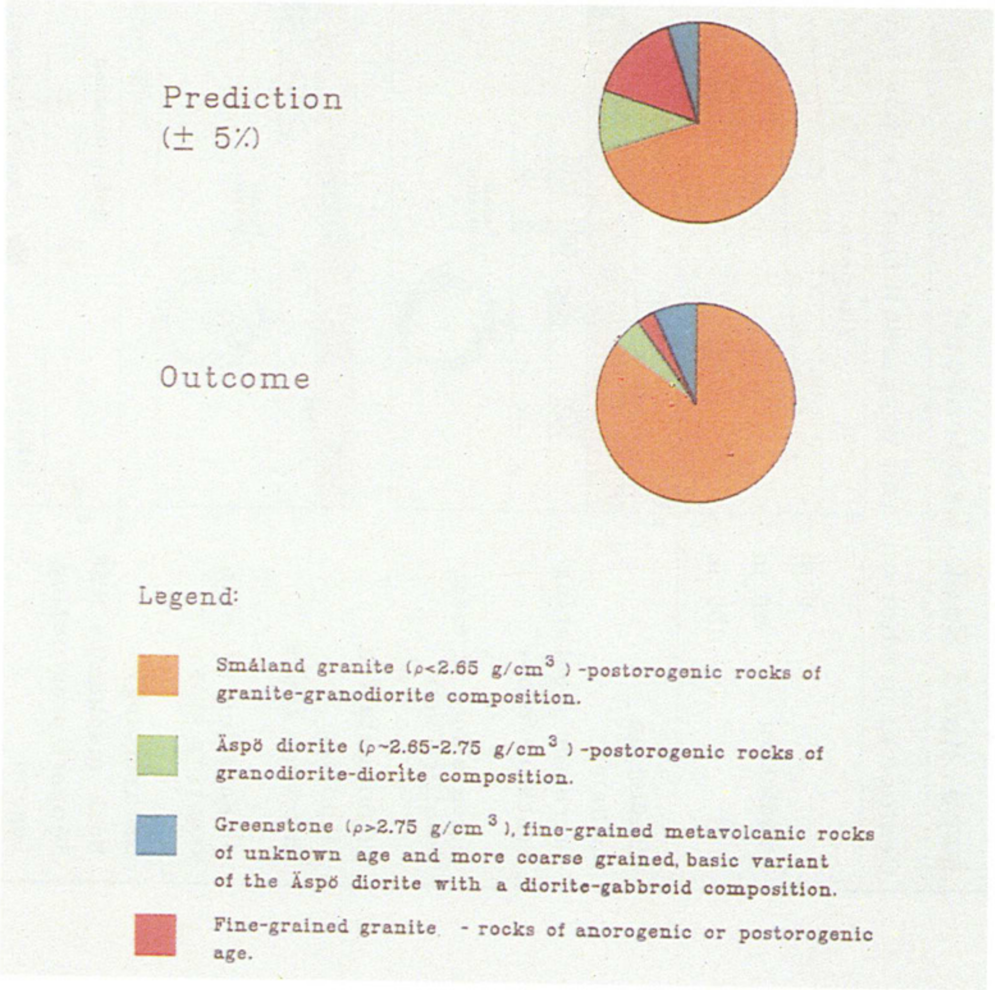


*Figure 6-2.* *Rock type distribution in section 0–700 m of the access tunnel.*

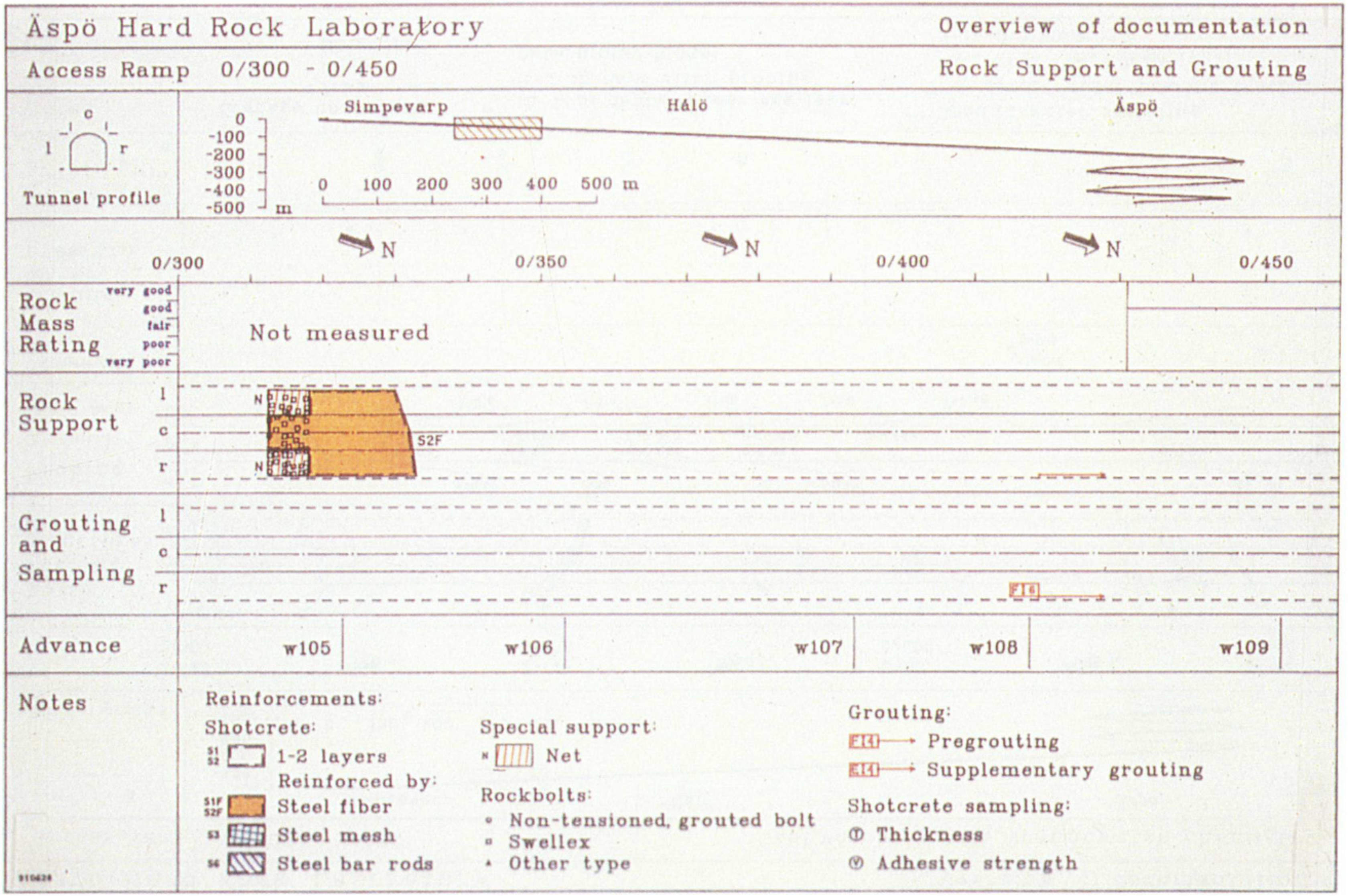


***Figure 6-3.*** *Example of overview showing rock support and grouting.*

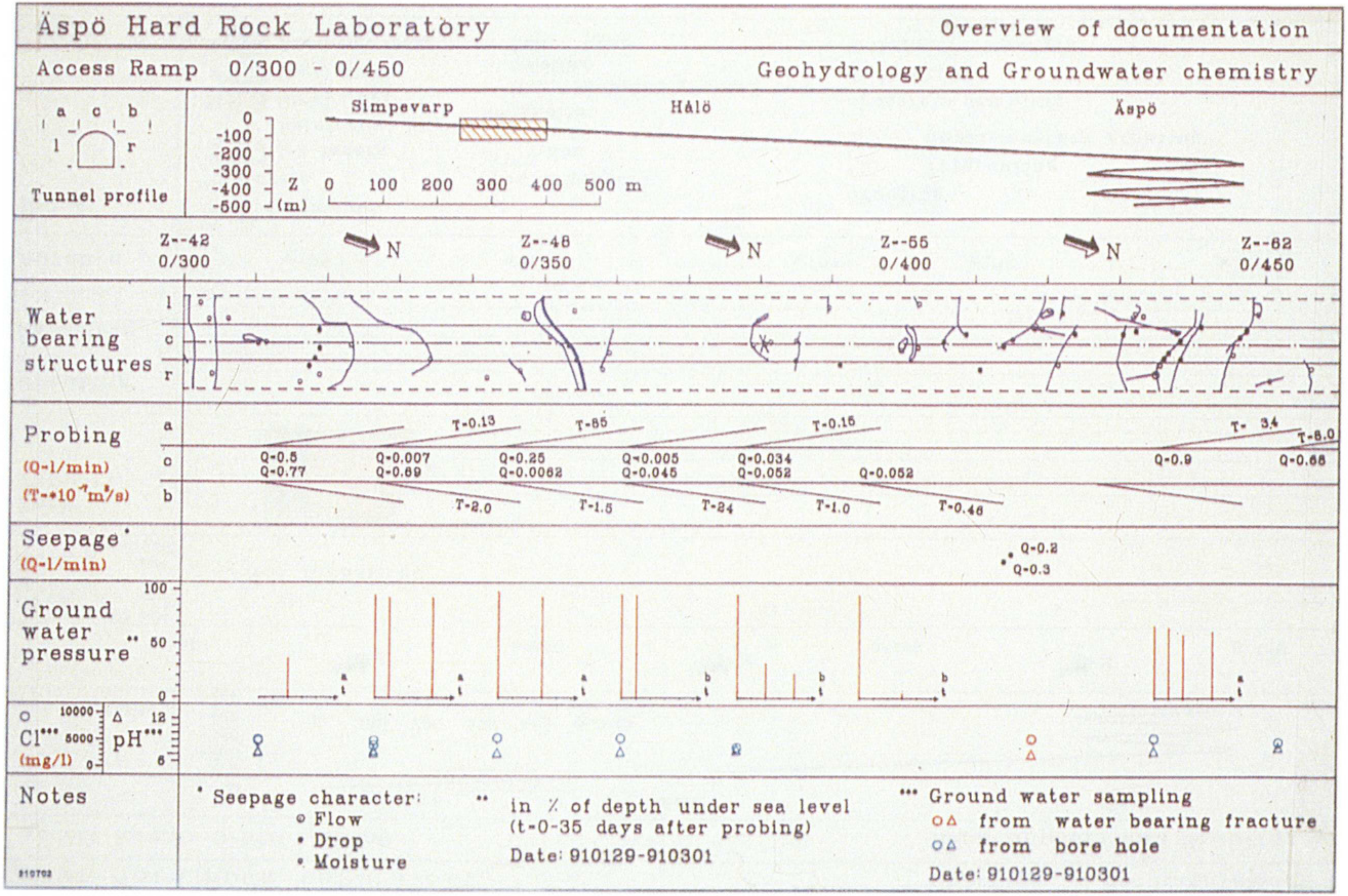


*Figure 6-4.* *Example of overview showing geohydrological and groundwater chemistry data.*

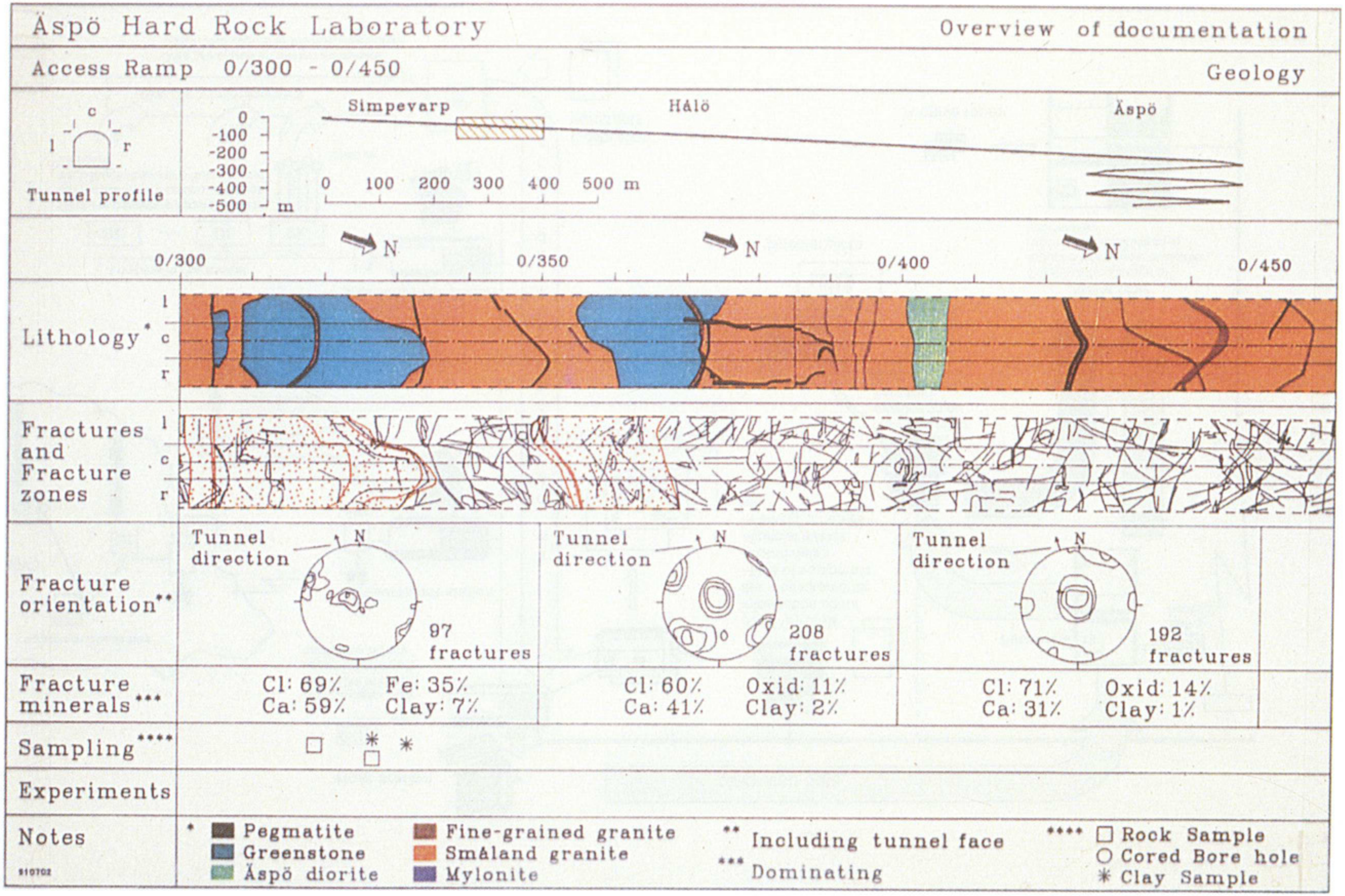


*Figure 6-5.* *Example of overview showing geological data.*

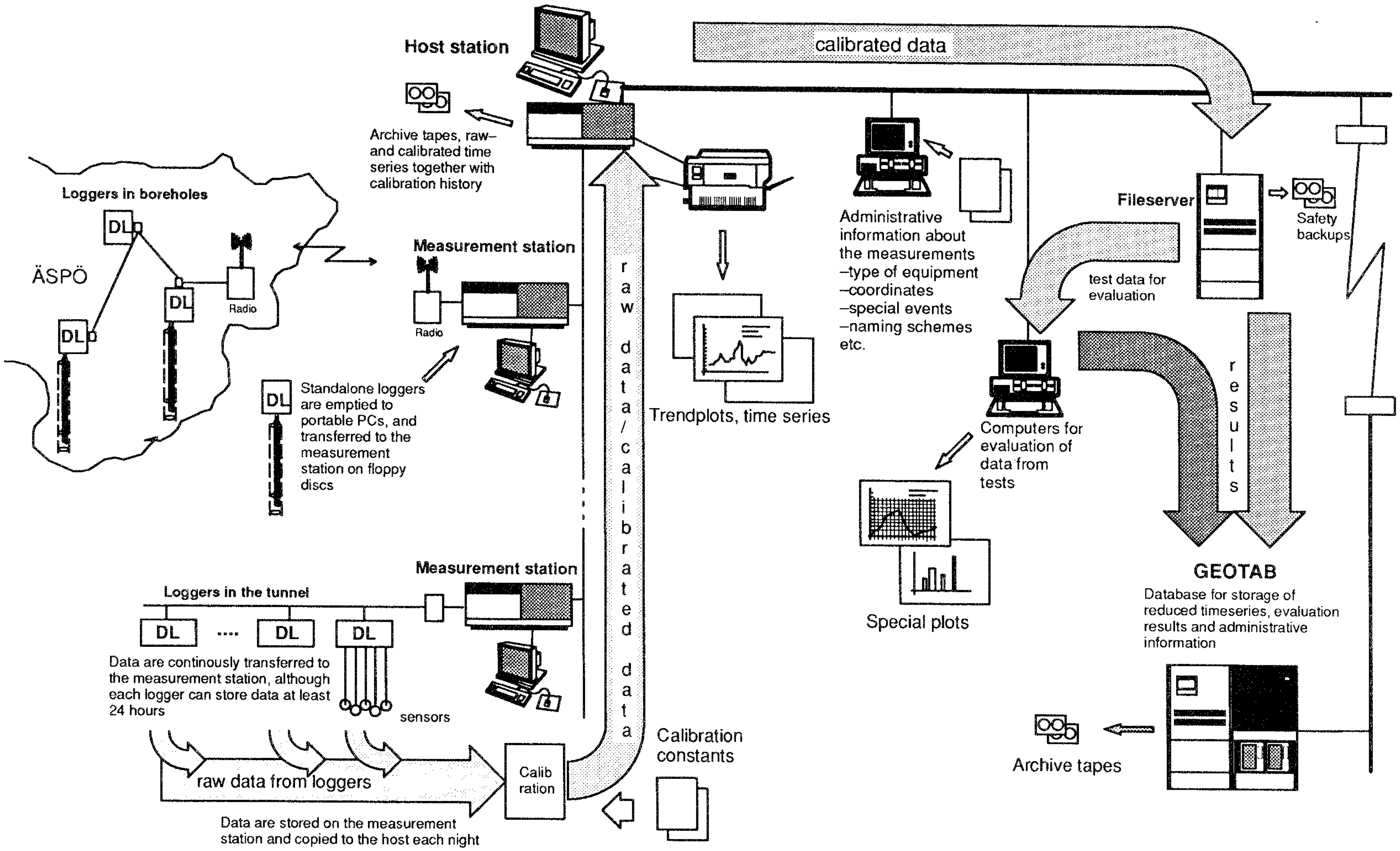


*Figure 6-6.* *An automatic system (HMS = Hydro Monitoring System) for monitoring groundwater pressures and flows has been set up for the Äspö Hard Rock Laboratory.*

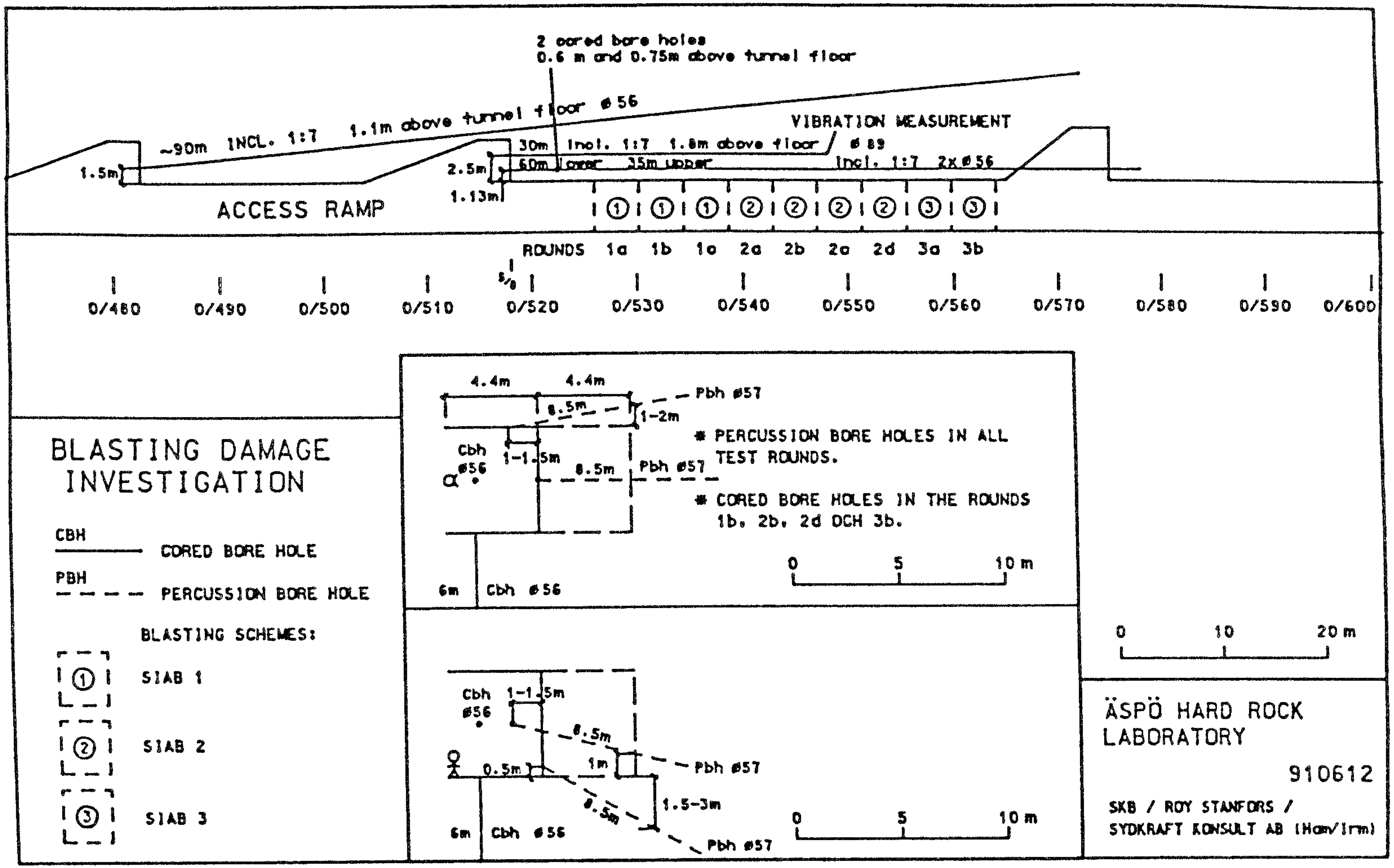


*Figure 6-7. Overview of blasting damage test.*

### Passage of zones

A special study has concerned the development of methodology for passage of fracture zones and related investigation activities.

The pre-investigations showed that the tunnel passes a large fracture zone at the south end of Äspö at a depth of about 180 m. Extensive preparations were made prior to the passage of the zone so that the passage could take place under controlled conditions with fulfilment of a number of subsidiary goals. The subsidiary goals include pinpointing of the location of the fracture zone, characterization of the zone and controlled pre-grouting – mainly with regard to the dispersal of the grouting compound. Passage of the zone NE-1 took place in the spring of 1992. The properties and location of the zone agree by and large with the predictions set up during the pre-investigations. The large water flows and pressures encountered in the zone required extensive sealing and rock support measures in order to permit safe passage of the zone. The work is under evaluation, but one of the conclusions from this zone passage is that the excavation technique for passing large water-bearing zones at great depth with high water pressures needs to be further developed. Considerable method development has taken place in conjunction with the preparations for passage of the NE-1 zone, among other things with regard to grouting of rock and measurement methodology. For example, special valve packs have been developed to ensure safety in connection with drilling and measurement of investigation holes.

### Dating of fracture zone movements

Within the general geoscientific research programme at SKB, fundamental studies have been conducted during the construction phase of the Äspö Hard Rock Laboratory regarding dating of the most recent observable movements in fracture zones. A comparative study of different methods has analyzed samples from the fracture zones EW-7, NE-4 and NE-3. The methods included have been paleomagnetic analysis, microstructural analysis, electron-spinner resistance (ESR technique) and various isotope ratios (K-Ar, Rb-Sr). In the case of NE-4, ESR technique shows the youngest dating, which corresponds to no movement having taken place for the past 1-2 million years. The paleomagnetic dating corresponds to a fault movement during the Carboniferous to Permian (345–225 million years ago). The K-Ar dating shows a slightly higher age /15/.

# 7 PROGRAMME FOR THE OPERATING PHASE - SUMMARY

After the construction phase, the operating phase will commence at the Äspö Hard Rock Laboratory. The operating phase will begin in 1995. It is assumed that experimental and demonstration activities will take place on the 460 m level. As data are obtained from the documentation during the construction phase, the expectation models on the rock mass at Äspö are updated. Experiments and tests are thereby planned in increasing detail for certain experimental drifts and niches.

A more detailed programme is presented in Appendix A with comments for the operating phase. Only a brief summary is given here.

## 7.1 GOALS FOR THE OPERATING PHASE

The operating phase shall meet the overall main and stage goals set up for the Äspö Hard Rock Laboratory. The requirements of stage goals 3, 4 and 5 shall primarily be met during this phase, see section 2.3.

## 7.2 EXPERIMENTAL AND DEMONSTRATION PROGRAMME 1995-1998

Proposed experiments and demonstration activities for the period 1995–1998 are presented in summary form in this chapter. The presentation is made in relation to the stage goals set up.

**Stage goal 3 - Test models for groundwater flow and radionuclide migration**

**Tests on detailed scale** – The movements of sorbing tracers can only be followed on a small geometric scale during the life of the laboratory. The experiments will be conducted in a borehole group where it is possible, after the experiments have been completed, to extract the rock in order to analyze the absorbed tracer on fracture surfaces. The test will therefore be conducted on fracture scale (5 m) and the models will be calibrated against hydraulic tests and tracer tests in the borehole group.

**Tests on block scale** – The purpose of this experiment is to study the flow distribution in a large individual fracture or a small fracture zone that can be expected to intersect a deep repository tunnel. The hydraulic connection between the zone and the fracture system in the sound rock is also of interest. In this experiment it is possible to calibrate the models against radar tomograms from salt injection tests in the same plane as the groundwater conductor. The experimental scale should be such that it is for the most part only possible to carry out experiments with non-sorbing or very weakly sorbing tracers. The test is therefore planned to be carried out on block scale, about 50 m. This scale is representative of the near field.

**Tests on site scale, regional zones** – Draft proposals for possible tests on a site scale and in regional zones are described in greater detail in Appendix A. These experiments are not planned to be commenced before the end of the 90'ies.

**Radionuclide retention** – Different experiments will be carried out to test, among other things, dissolution and retention of radionuclides in situ. A special chemical probe, the CHEMLAB probe, has been developed for these experiments. Some experiments will be carried out on material samples in the probe with the probe situated in a fracture zone. The intention is to utilize the zone that has been characterized within the experiment "Tests on block scale". Previous investigations have shown that solubility, sorption on fracture surfaces and diffusion into the rock matrix reduce the dispersal of radionuclides in the bedrock. However, the data and models that describe the chemical properties of the radionuclides in the natural bedrock environment are based for the most part on laboratory tests. It is difficult for such tests to simulate, for example, natural reducing conditions, the natural concentration of colloidal particles, the natural content of microbes and dissolved gases. All of these conditions are of extremely great importance for the rock as a barrier, i.e. they have a great influence on the solubility or retention of radionuclides if radioactive waste is exposed to groundwater.

**Redox reactions** – A large-scale redox test is currently being conducted to show that the redox capacity of the rock is sufficient in the flow paths. Reducing conditions at repository depth are a prerequisite for long canister life. The groundwater that has been sampled on different occasions and at different places within the study site investigations has always proved to be reducing, proving the reducing properties of the rock. However, the kinetics of the redox reactions between the minerals in the bedrock and the groundwater needs to be further elucidated. These reactions are being studied during the construction phase, when oxidizing water can get down into the facility. Similar investigations are being conducted on the block scale (several tens of metres), which permits a check of all relevant parameters at the same time as it permits an assessment of the rate of the exchange reactions. The overall purpose of the investigations is to determine the reaction kinetics when oxidizing water is converted into reducing water by correlating the flow rate with mineralogical changes.

Experience from groundwater analyses from boreholes indicates the presence of bacteria in the majority of the samples. This may be due to contamination during drilling and other procedures preceding sampling. A separate sub-project during the operating phase is aimed at answering the question of whether bacteria are present in undisturbed rock, and if so which species dominate. Furthermore, the living conditions of the bacteria will be studied, along with how large a portion of the bacteria adhere to fracture surfaces.

Microbes will be generally investigated in conjunction with the work done within the framework of tests aimed at redox kinetics.

**Disturbed zone** – It is a known fact that the excavation of a tunnel in fractured crystalline bedrock affects the hydraulic properties immediately outside the tunnel wall. The causes of the disturbance have been interpreted as redistributions of stresses, blasting damages and chemical reactions. Furthermore, two-phase flow, due to drying-out and degassing of the groundwater, has been offered as a possible explanation. The consequences of the combination of these phenomena and perhaps a few others are currently poorly understood. Experiments in the disturbed zone will be conducted to understand and explain these phenomena and to see if they will persist in a backfilled deep repository.

**Numerical models** – Numerical modelling of groundwater flows and groundwater levels has been an integral part of the Äspö Hard Rock Laboratory from the very beginning. Originally, the modelling was begun with a simple generic modelling of different alternative designs of the laboratory and with the saline water front problem. Gradually the models were refined into a comprehensive prediction model of the access tunnel and its effects on groundwater levels and water flux. The access tunnel is currently under construction and the model is being tallied against data obtained during the construction phase.

Groundwater modelling will continue to be an important part of the project. Transport and flow modelling is currently under way for the purpose of refining the existing models and including solute transport in a more comprehensive fashion. The planned experiments will be integrated as much as possible with the development of conceptual and numeric models. A principal task is to successfully model the planned experiments.

For the purpose of coordination between experimentalists and model developers, a Task Force has been formed during the construction phase with members from the participating international organizations. The Task Force will follow a number of modelling projects linked to the experiments.

**Stage goal 4 – Demonstrate construction and handling methods**

The purpose of the programme is to demonstrate how the construction of a repository will take place. In conjunction with the construction of a deep repository, it is necessary to carry out a number of investigations to obtain information for designing the repository, for sealing the repository and for the final safety assessment of the completed repository. The execution of the investigations is dependent on the choice of repository system.

Today it is assumed that the repository will be built at a depth of about 500 m. Extensive experience has been obtained from previous SKB studies with regard to instruments and methods for characterization of the near field. This applies above all to the results of the cooperative research in the Stripa project (radar, seismics and hydraulic measurements, etc.). The investigations of the study sites have also contributed towards improving skills in characterizing the near field. Tunnelling projects in Sweden and abroad have also provided a great deal of practical experience. The above knowledge notwithstanding, a complete demonstration of how the characterization of the near field in a deep repository is carried out is lacking. It is important to demonstrate this on a natural scale.

Besides methodology for characterizing the near field, a developed technique is required for passage of water-bearing zones under high hydraulic pressures, as well as a developed grouting methodology. Certain supplementary construction work may be required for these development efforts.

**Stage goal 5 – Test important parts of the repository system**

This programme entails conducting relevant pilot and demonstration tests after the main principles for repository design and systems have been established in the mid-90s. The purpose of the tests is to demonstrate repository performance by clarifying the interaction of the rock and the selected buffers under realistic conditions that can be expected to prevail in deposition facilities.

## 7.3 SCHEDULE FOR THE OPERATING PHASE

The programmes presented do not have clear lines of demarcation in relation to each other, so coordinated planning is necessary.

Up until 1995, the different sub-projects will be planned in detail with respect to goals, analysis methods, instruments, evaluation, resources etc.

New international research findings, new repository concepts or results achieved at the Äspö Hard Rock Laboratory may give rise to changes in research and demonstration requirements. It is therefore important that there be some degree of flexibility for the detailed planning of the operating phase.

Figure 7-1 shows a general logistics plan and schedule for the operating phase at the Äspö Hard Rock Laboratory.

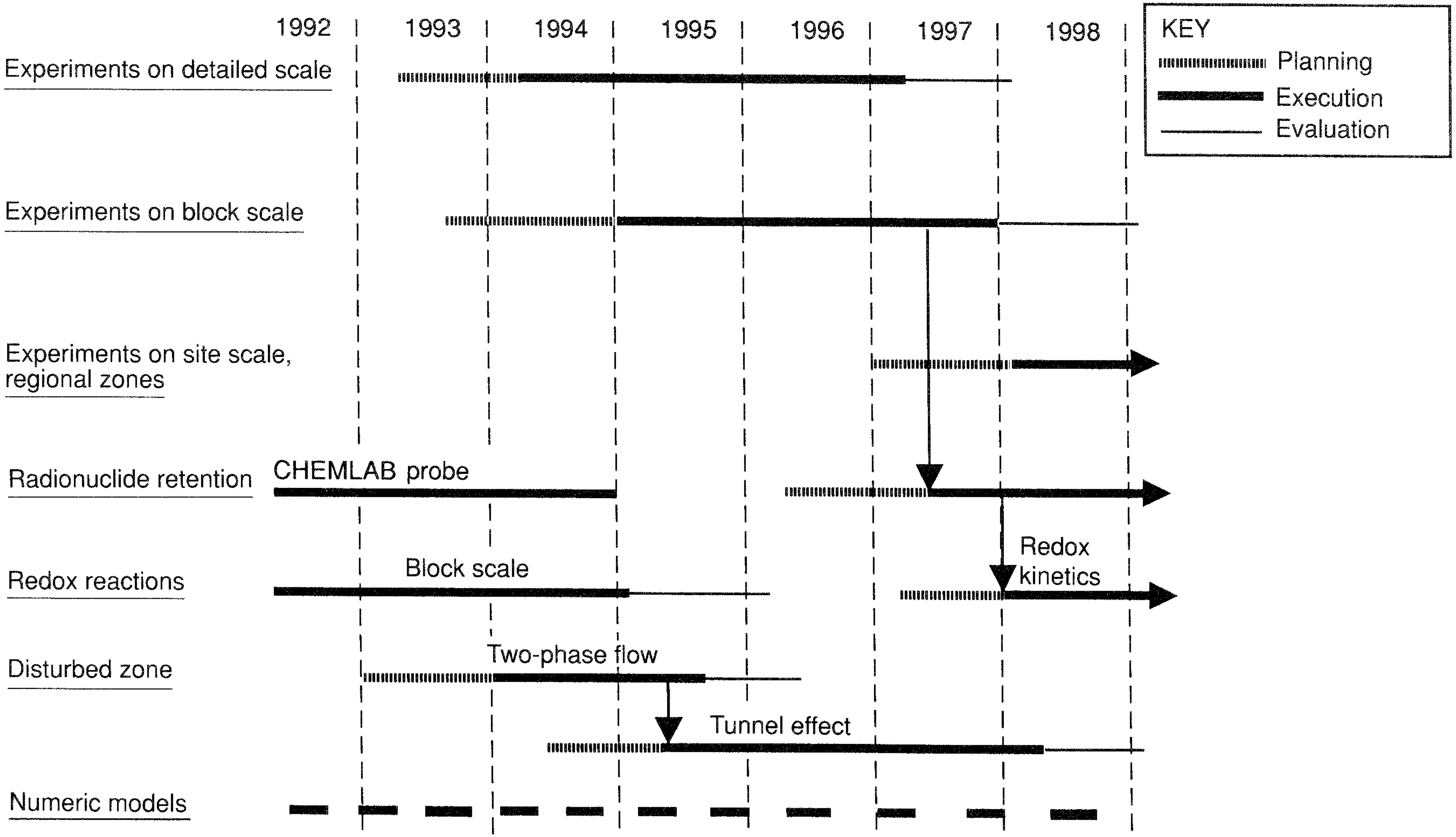


***Figure 7-1.*** *Logistic plan and timeschhhedule for planning and execution of the Äspö Hard Rock Laboratory's operating phase, tests of models for groundwater flow and radionuclide migration.*

# 8 EXECUTION

## 8.1 ORGANIZATION

Like SKB's other R&D projects, the R&D work at the Äspö Hard Rock Laboratory is being executed mainly through contracts to universities, colleges, research institutes, consultants, industrial companies and other Swedish and foreign researchers. This makes it possible to achieve a high standard of quality and competence, since the most qualified experts can be chosen for different investigations and experiments. Different alternative approaches or models can be tried for some questions.

The direction and contents of the Äspö Hard Rock Laboratory programme are determined by a Programme Committee within SKB's Research and Development unit. With the RD&D-Programme as a basis, annual planning reports are published which describe in some detail the work to be done during the coming year. Two reference groups are associated with the project. The first, the Scientific Advisory Committee, is supposed to review the research activities from a technical/scientific viewpoint and serve in an advisory capacity. The other group, the Construction Advisory Committee, reviews and gives advice on construction-related matters. International cooperation is coordinated by a "Technical Coordinating Board".

The project is headed by a Project Manager within SKB's Research and Development unit. A project group is in charge of executing the work. Principal Investigators in charge of geology, hydrogeology, geochemistry, instruments and construction issue recommendations for overall programmes, draw up object plans, analyze and evaluate results etc. The site office group carries out field surveys and furnishes information to the general public and specialists. Different sub-projects are defined as the need arises to achieve good coordination. The organization also includes project administration as well as planning and follow-up of the construction and civil engineering activities. Planning of the experimental and demonstration activities for the operating phase is also included.

At present the site office is temporary, located near the tunnel entrance at the Simpevarp facilities. During 1993–1994 a permanent research village will be built on Äspö, which will have direct access to the laboratory through an elevator shaft.

## 8.2 REPORTING

Results etc. are documented continuously in written reports. Most of the publications are in English. The principal results and analyses are summarized in SKB's report series "Technical Reports" (TR). These reports are based on preliminary analyses and data compilations in "Progress Reports" (PR). RD&D results are often compiled first in "Technical Notes" to facilitate rapid internal reporting. Six Technical Reports and 112 Progress Reports had been published as of August 1992. Besides in SKB's own report series, the project and its results are also presented in international journals and at international conferences and symposia.

## 8.3 QUALITY ASSURANCE OF DATA HANDLING AND ANALYSIS

Quality assurance (QA) within a project can be defined as making sure that all activities are executed in a carefully planned and well-specified manner. Target specifications for e.g. organization, administration, analyses and equipment shall be complied with and remain unchanged until such time as new decisions may be made by the authorized individuals. For a research programme, it is of the utmost importance that data handling take place in a controlled fashion. The Äspö Hard Rock Laboratory project has been characterized from the start by carefully specified documentation and data collection. In preparation for the continued construction work and experimental activities, a quality manual is being prepared containing instructions for procurement of goods and services, documentation, record-keeping, quality control, non-conformance reporting etc.

The QA programme shall, besides benefiting the Äspö Hard Rock Laboratory, be regarded as a necessary "dress rehearsal" for the construction of the deep repository for radioactive waste.

## 8.4 INTERNATIONAL PARTICIPATION

International consensus and experience exchange across the borders is essential within the field of radioactive waste management. The Äspö Hard Rock Laboratory has attracted strong international interest and cooperative agreements have been concluded with a number of international organizations who wish to participate in the project. Agreements have been signed with the following: Atomic Energy of Canada (AECL), the Power Reactor and Nuclear Fuel Development Co. of Japan (PNC), the Central Research Institute of the Electric Power Industry of Japan (CRIEPI), Teollisuuden Voima Oy of Finland (TVO), Agence Nationale pour la gestion des Dechets Radioactifs of France (ANDRA) and NIREX of Great Britain. The formal signing of an agreement with the US Department of Energy (DOE) is expected to take place during 1992.

The international participation in the project is being coordinated by the "Technical Coordinating Board" (TCB). Scientific exchange is taking place through participation in the "Scientific Advisory Committee" (SAC). TCB can, when necessary, form "Task Forces" (working groups) for special scientific tasks. Recently a Task Force with international participation was created for hydraulic modelling of groundwater flow.

Practical cooperation can take the form of the organizations' having personnel on the site (PNC and CRIEPI), testing of instruments (ANDRA) or development and testing of models for groundwater flow and transport of solutes (PNC, CRIEPI, US/DOE, ANDRA, TVO, NIREX).

## 8.5 INFORMATION

Information on the Äspö Hard Rock Laboratory is an important and integral part of the project. It is handled in keeping with SKB's general information policy, which means it shall be open, objective, comprehensive and up-to-date.

A number of target groups can be defined that make different demands on the content and form of the information. These target groups include: the general public, SKI, Oskarshamn Municipality, the County Administration in Kalmar County, participating international organizations, the research community and, not least, those who, in one way or another, participate in the actual work.

Information boards have been set up on Äspö and a visitors' niche has been arranged under ground near the tunnel entrance. A brochure has been published. A videofilm is under production.

Approximately 2000 people visited the Äspö Hard Rock Laboratory's site office during 1991. 23 nations were represented.

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APPENDIX A

# PROGRAMME FOR INVESTIGATIONS AND EXPERIMENTS DURING THE OPERATION PHASE

# CONTENTS

# 1 INTRODUCTION

After the construction work for the Äspö Hard Rock Laboratory is concluded, a number of experimental and demonstration tests will continue at the Äspö Hard Rock Laboratory. The planning for the operating phase began in 1988 and will continue with gradually increasing detail. The programme during the operating phase will be affected by SKB's other research results and the requirements that are associated with long-term safety aspects and the construction of the deep repository.

# 2 GOALS FOR THE OPERATING PHASE

The operating phase shall fulfil the overall main and stage goals that have been set up for the Äspö Hard Rock Laboratory. In particular, stage goals 3, 4 and 5 shall be met during the operating phase. In other words, the RD&D activities shall:

**3 Test models for groundwater flow and radionuclide migration**

- refine and test on a large scale at repository depth methods and models for describing groundwater flow and radionuclide migration.

**4 Demonstrate construction and handling methods**

- provide access to rock where methods and technology for guaranteeing high quality in the design, construction and operation of a deep repository can be refined and tested, and

**5 Test important parts of the repository system**

- test, investigate and demonstrate on a full scale different components that are of importance for the long"term safety of a deep repository system.

# 3 COMMENTS ON THE GOALS OF THE OPERATING PHASE

Based on the above goals, three basic types of RD&D activities can be defined:

- Qualitative and quantitative description of physical and chemical processes that are of importance for the performance and safety of the repository.
- Methodology for adapting the repository to the local properties of the rock.
- Demonstration and validation of technology for pre-investigation, detailed characterization, and construction and handling.

There are also questions of a scenario nature on which the work at the Äspö Hard Rock Laboratory can shed some light. One example is the probability and consequences of future rock movements.

In the practical execution of the research programme, the three main types of RD&D activities will overlap each other. For example, the research on the processes that govern nuclide transport through the rock is dependent on the methods that are available for characterizing the rock. Similarly, the methodology for adapting the repository to the rock is dependent on the available pre-investigation methods and on the relative importance of different transport processes.

## 3.1 PHYSICAL AND CHEMICAL PROCESSES

A safety assessment is based on a description and a numerical modelling of the processes that could conceivably be of importance for the transport of radionuclides from the spent fuel to the biosphere. The research in the Äspö Hard Rock Laboratory should attempt to confirm (validate) by means of field tests the assumptions made in more recent safety assessments and develop more realistic models than the simplified models that are used today.

The following physical and chemical processes can be studied through a combination of field tests (in the Äspö Hard Rock Laboratory), laboratory tests and numerical modelling:

- Nuclide transport in fractured rock. Experiments will be conducted where groundwater flow and nuclide transport are studied on different scales. Important questions are, for example, the flow geometry in fracture zones and individual fractures, quantification of transport parameters such as dispersion, capacity for sorption (flow-wetted surface area) and matrix diffusion, and possible connections between geological structure and permeable fractures (the influence of heterogeneity on flow and transport).
- Influence of the disturbed zone around drifts and deposition holes. A better qualitative and quantitative understanding of the processes that make the hydraulic conductivity around a drift separate from that in the undisturbed rock. (Axial/radial conductivity, two-phase flow, stress redistribution, blasting damages, backfilling of the repository.)
- Groundwater chemistry and its influence on the solubility and sorption of radionuclides.
- Interaction between rock and buffer material. (Swelling pressure, chemistry, influence of impurities (oil, bacteria), backfilling of the repository, durability.)
- Thermal impact of the spent fuel waste on groundwater chemistry and hydraulic properties of rock and buffer material.
- Influence of the repository on groundwater flows and groundwater chemistry during the construction and operating periods and possible consequences after backfilling of the repository.
- Long-term mechanical stability of the repository. (Deformation and outcome in drifts and deposition holes.)

## 3.2 METHODOLOGY FOR CONSTRUCTION

Progressively more detailed knowledge on the rock will be obtained during the construction of a repository. For safety- and construction-related reasons, the detailed layout of the repository will have to be adapted to the local geological conditions. To do this, a carefully thought-out plan for pre-investigation and design is required, along with well-supported criteria for making the necessary decisions. Criteria are needed, for example, to determine the exact location of canisters/deposition holes, repository tunnels, support and grouting measures and plugs in drifts. An integrated detailed characterization methodology is required based on pilot holes in front of planned drifts and investigations in drifts. Instruments and interpretation methods need to be refined and their applicability demonstrated. Development of special instruments may also be required in order to carry out experiments related to the description of different physical and chemical processes.

The following main projects are thus planned:

- Formulation of a plan and an integrated investigation programme for detailed characterization of a projected repository area as a basis for the layout of the repository, choice of locations for canisters and performance and safety assessment. The programme will be carried out to demonstrate its function at different stages during the construction of a projected repository. Important questions to answer include: With what certainty can fractures/zones of different orientation and character be identified at a given distances from an investigation/deposition hole/tunnel?
- Optimization of investigation plan to progressively reduce the uncertainty in the site-specific safety assessment. The optimization will be done against the background of a cost/benefit analysis.

## 3.3 DEVELOPMENT AND DEMONSTRATION OF ENGINEERED BARRIERS

The process of canister deposition and backfilling with bentonite and bentonite-sand mixtures includes various handling steps that must be designed in detail in accordance with physical tolerances as well as with consideration given to possible variations in ambient conditions, such as humidity and water seepage. The central purpose here is to guarantee the conditions assumed in the safety assessment. It must be possible to verify the required quality in the results after deposition, e.g. the imperviousness of the bentonite and the exact position of the canister, by means of post-deposition measurements. Various steps in the handling chain can be developed and tested in the Äspö Hard Rock Laboratory.

The safety assessments KBS-3, SKB 91 etc. describe the functions that are important in the deep repository in order to achieve long-term isolation. Some of these are based on the quality of the engineered barriers. Certain prerequisites for fulfilling the necessary performance criteria can also be studied by means of long-term tests in the Äspö Hard Rock Laboratory.

The Äspö Hard Rock Laboratory can thus be utilized to determine the details of the actual deposition procedure. Besides making sure that machines and other equipment work right, it is necessary to drill the operators and give them an idea of what practical problems they must be able to solve in a real operating situation. This requires training with equipment under as realistic conditions as possible. Training in a non-radioactive environment would seem to be fully adequate.

The Äspö Hard Rock Laboratory can also be used to study the short- and long-term performance of the engineered barriers. Part of this performance is a function of the practical execution of the deposition, another is dependent on the properties of the bentonite and the rock. The execution of deposition can be checked by means of measurements. The bentonite and the properties of the near field must be tested by means of model calculations that are progressively refined. The results are followed up through trials and tests. By means of full-scale tests in the Äspö Hard Rock Laboratory, it is possible not only to document data and knowledge, but also to ensure adequate safety by enabling the activities to be "rehearsed" prior to application in the deep repository.

# 4 TEST OF MODELS FOR GROUNDWATER FLOW AND RADIONUCLIDE MIGRATION

## 4.1 BACKGROUND

In order for a siting application to be written and approved, it must be possible to demonstrate the long-term safety of a repository. This requires knowledge of the processes that govern groundwater flow and radionuclide migration, as well as site-specific data on important transport parameters.

Groundwater flow and transport in fractured rock have been studied intensively within the framework of SKB's R&D programmes during the past 15 years. The site investigations, which have been conducted on many different sites in Sweden to date, have resulted in a comprehensive database that provides a good idea of the general structure and hydraulic properties of the crystalline rock. The hydraulic properties of fracture zones have been investigated in Stripa, Finnsjön and Äspö by means of hydraulic cross-hole measurements (interference tests). This has yielded knowledge on the heterogeneity and hydraulic interconnection of fracture zones over distances of several hundred metres. Within the framework of the international Stripa project, techniques such as borehole radar and cross-hole seismics have been developed for locating and characterizing fracture zones. These techniques have greatly expanded the options available for making reliable structural descriptions of large rock volumes. Together with the development of hydraulic measurement and modelling methods, this has considerably increased our knowledge of groundwater flows and flow paths in a fractured rock mass.

Tracer tests to investigate the transport of solutes have been carried out in Studsvik, Finnsjön, Stripa and now, most recently, in the Äspö Hard Rock Laboratory. These tests have yielded a more accurate picture of the groundwater flow in the rock, especially the distribution of the water flow in fractures and the flow pattern in these fractures. In-situ tests with sorbing tracers have been conducted within the framework of SKB's R&D-programmes in Stripa. In these tests, sorbing nuclides were injected in a fracture plane. The presence of injected nuclides could only be detected a few decimeters from the injection point approximately one year after the conclusion of the experiment.

Despite the experience gained thus far, the knowledge base needs to be further improved, above all with regard to the processes that govern the transport of solutes and the variability in the governing parameters. Even though several tracer tests have been conducted thus far, relatively few in-situ data exist on important transport parameters such as flow porosity and its heterogeneity in the fracture system (which determines the velocity of the groundwater), dispersion, matrix diffusion and the fracture surface that is available for sorption of radionuclides (the flow-wetted surface area). Representative data on these parameters are required from the near rock around a canister, the sound rock near the final repository tunnels and conductive fracture zones further away. For this reason, in-situ experiments are planned on several scales to obtain data on these parameters and their variation along a hypothetical flow path from the repository to the biosphere.

Several experiments are planned to obtain further knowledge of the chemical processes that control the transport of radionuclides through the rock. The models that have been used to describe these processes have primarily been based on laboratory tests. There is thus a need for in-situ tests to validate models and check the parameter values used in the models.

Flow and transport in the disturbed zone around drifts comprises a special problem complex. Excavation of a hole in the rock, such as a drift, entails a disturbance in the surrounding rock which causes a change in the hydraulic properties of the rock. Several different physical and chemical processes have been identified which are apparently of importance for the hydraulic properties of the disturbed zone. The relative importance of different processes and the dependence of the hydraulic properties on the excavation method and geological conditions have not been satisfactorily explored. A series of experiments is planned to illustrate the importance of the disturbed zone in connection with the construction of the deep repository and its long-term safety performance.

A programme for development and application of numerical models for groundwater flow and transport of solutes is being coupled to the experimental programme defined for the Äspö Hard Rock Laboratory. Several of the experiments that will be conducted in the Äspö Hard Rock Laboratory are aimed at providing data for validation of these numerical models.

## 4.2 TESTS ON DETAILED SCALE

### 4.2.1 Background

The transport of most solutes takes place more slowly than the average flow velocity of the groundwater. This is due to a number of different processes that give rise to a retardation of the solutes in relation to the flowing groundwater. Important processes are dispersion and retention. Retention, or retardation, is caused by the fact that radionuclides sorb on mineral surfaces in contact with the flowing water and the fact that radionuclides diffuse out from water-bearing fractures to the stagnant water in the microfissures in the rock and are sorbed on the mineral surfaces there. Non-sorbing substances are also retarded by diffusion to the stagnant water in the microfissures in the rock and are thereby withheld from the transport in the running water.

The retention of sorbing nuclides compared with non-sorbing solutes is dependent on how strong the sorption equilibrium is and on how much sorbing ("flow-wetted") surface area there is in relation to the water volume. In the case of transport in fractured rock, the relationship between the surface area that is available for sorption and the water flow is also of importance.

The purpose of the in-situ experiments on the detailed and block scales is to obtain data that quantitatively describes the various processes and their relative importance in different fractures and flow regimes.

Fundamental to the description is a good notion of how the groundwater flow is distributed in a fracture plane. The flow distribution determines the variations in flow velocity and thereby the dispersion. It also determines the surface area that comes into contact with the running water and thereby the surface area that is available for sorption. This surface area is often called the "flow-wetted surface area".

Obtaining data on the flow-wetted surface area, i.e. the fracture surface that is in contact with the running water, is a difficult task. A direct measurement of the flow-wetted surface area requires injection of sorbing tracers and/or some type of dye or gel in a fracture, which is then carefully excavated. This type of experiment is important for showing the distribution of the flow-wetted surface area in the fracture plane and the fact that matrix diffusion is an important process for the retardation of radionuclides. Experiments of this type are time-consuming and costly, however, and can only be conducted on a limited scope in conjunction with the detailed characterization of a future final repository. It is thus also important to develop and demonstrate indirect observation methods for the important transport parameters which can be utilized in the characterization of a final repository. Such experiments are based on hydraulic tests and tracer tests with non-sorbing solutes. In both cases, a number of experiments are being conducted to obtain statistics on the variation in the transport parameters.

### 4.2.2 Goals

The main goals of this project are:

- to determine the parameters and the processes that govern the transport of sorbing nuclides in individual fractures, and
- to obtain knowledge on the variability of the transport parameters for fractures of different character.

### 4.2.3 Possible experimental design

To demonstrate that matrix diffusion is an important process for retardation of radionuclides and to obtain a body of data, one or more experiments will be conducted where sorbing tracers are injected into a fracture over a long period of time. Potentially suitable fractures are selected primarily on the basis of tunnel mapping data. A hole is drilled that intersects a suitable fracture at such a distance from the drift that the complication entailed by the disturbed zone is avoided. Sorbing tracers (e.g. caesium and strontium) are injected continuously over a long period of time (several years). The test is concluded with injection of a dye, gel or epoxy. An overcoring or careful excavation of the fracture plane is then performed. The distribution of the dye (or equivalent) in the fracture plane indicates the extent and shape of the flow channels. The fracture surface is then sampled to determine the in-diffusion profile in the rock matrix.

The in-situ tests will be supplemented with laboratory tests where tracer tests with sorbing tracers are performed on actual fractures taken from the Äspö Hard Rock Laboratory. In this case the tests can be conducted under well-controlled conditions where the flow, the flow-wetted surface area, porosities, sorption properties etc. are known. Breakthrough curves and in-diffusion profiles in the matrix are determined from the tests.

To demonstrate the capabilities of indirect methods to produce in-situ data on important transport parameters, an experiment with non-sorbing tracers will also be performed on a detailed scale. This experiment is based on drilling 10–12 holes through a well-defined fracture within a relatively small area. The transmissivity distribution in these holes will provide an estimate of the fraction of the fracture surface where flow takes place (the "flow-wetted surface area"). Hydraulic cross-hole tests and tests with non-sorbing tracers will be performed to determine the flow relationships in the fracture plane. By performing tests with different gradient directions, flow velocities and different distances and directions between injection and sampling holes, it is possible to obtain data on longitudinal and transversal dispersion, matrix diffusion and, to some extent, the scale dependence of these parameters. Diffusion to areas with stagnant water can be investigated by conducting tests with tracers of different particle size.

Since channel distribution and flow-wetted surface area are important parameters, investigations will also be carried out to try to quantify these parameters by means of independent methods. Studies will be conducted to determine to what extent it is possible to estimate these parameters on the basis of measurements in individual boreholes and/or observations in tunnels. Of special interest is whether data from tunnels can be considered to be representative of the undisturbed rock.

To obtain a good idea of the variation of the transport parameters depending on geological conditions, similar experiments should be performed on 4-6 individual fractures or small fracture zones in different parts of the Äspö Hard Rock Laboratory. The investigations should be focussed on fractures belonging to the dominant fracture sets on Äspö.

## 4.3 TESTS ON BLOCK SCALE

### 4.3.1 Background

According to the present concept, a future deep geological repository will be configured in such a manner as to avoid major water-bearing zones. Based on the knowledge of the occurrence of water-bearing zones that has been gained thus far, individual water-bearing fractures or minor zones can be expected to intersect the tunnels in a deep repository. Containers of spent nuclear fuel are intended to be placed in the "good" rock at a suitable distance from minor water-bearing zones. This experiment is aimed at characterizing such minor water-bearing zones and their connection to the fracture system in the surrounding "good" rock. The experiment will thus yield valuable data on possible radionuclide transport from the deposition hole to permeable fractures in the surrounding rock. The experiment will therefore be conducted on a scale that can be considered representative of the rock surrounding the spent fuel containers.

### 4.3.2 Goals

The goals of this sub-project are:

- to characterize the groundwater flow and transport in a minor fracture zone or a water-bearing fracture of large extent and its hydraulic connection with surrounding fracture networks, and
- to prepare the experimental area for the experiment "Radionuclide retention".

### 4.3.3 Possible experimental design

The subject of study in this sub-project is a large individual fracture or a small fracture zone (metre-scale thickness) with an approximate extent greater than about 30 m. The part of the fracture zone studied within the project shall be situated at least 10–20 m from any drifts to avoid disturbances of the experiments. A fracture zone with these dimensions will probably not occur in isolation, but will be intersected by several small water-bearing fractures, which means that this project cannot be designed as a study of an individual fracture. Instead, the characterization of the experimental area and the experimental set-up must be done in three dimensions, even though flow and transport will probably be dominated by an individual fracture or minor fracture zone.

The dominant fracture that is the target of the investigations is assumed to be more or less perpendicular to any existing drift. A 40–50 m long instrument drift is excavated parallel to the fracture zone at a distance of about 20 m from the plane of the fracture zone.

From the instrument drift, 10–15 holes are drilled so that a relatively even distribution of the boreholes is obtained on a portion of the fracture plane with an approximate size of 30 x 30 m. After an initial characterization of the fracture system, the boreholes are equipped with a packer system that permits all boreholes to be divided into several measurement sections. The borehole sections shall isolate the fracture zone, but also other water-bearing fractures that are intersected by the boreholes. It can be assumed that the test sections will be relatively evenly distributed over the cube constituted by the experimental volume. The characterization of the tracer transport will thus be three-dimensional.

A number of non-sorbing and weakly sorbing tracers are injected in some of the boreholes while the tracer concentration is measured in surrounding borehole sections. Injection is done sequentially in several of the boreholes in order to obtain a good picture of the flow distribution in the fracture zone and the surrounding rock. Injection of tracers takes place both in the fracture zone and in the surrounding "good" rock. During the course of the experiment, the chemical composition of the groundwater is checked at regular intervals to see whether the experiments have caused any changes. In the final phase, saline or fresh water is injected into the fracture zone and radar tomography measurements are made in the plane of the fracture zone to obtain independent data on the flow distribution in the fracture plane.

The field tests will be preceded by laboratory experiments to try out very weakly sorbing tracers suited for this test.

The experiments are expected to yield valuable data on the transport parameters for minor fracture zones and the surrounding "good" rock as well as a necessary frame of reference for the sub-project "Radionuclide retention", see section 4.6, which will later be carried out at the same place.

## 4.4 TESTS ON SITE SCALE

### 4.4.1 Background

At least some local fracture zones can be expected to intersect the rock volume that will be selected as a repository area in the future. The repository is designed under the assumption that the canisters are positioned at a given distance from local fracture zones. One of the goals of this sub-project is to obtain data for better determining the minimum distance required to local fracture zones, based on the site-specific transport properties.

The project will also be a test of our ability to detect and characterize local fracture zones. This is directly linked to the project for rock volume description and the development of strategies for design-as-you-go of a repository.

Construction and operation of a deep repository will entail drainage of the rock volume during a long period of time, perhaps 50 years, before the repository is sealed.

This drainage will give rise to changes in the groundwater chemistry due to the fact that surface water will move towards deeper levels. The Äspö Hard Rock Laboratory entails a drainage equivalent to that which can be expected from a future deep repository. Initiating a forced drainage would make it possible to study the geochemical changes during a shorter span of time than would otherwise have been the case.

### 4.4.2 Goals

The goals of this sub-project are:

- to characterize groundwater flow and radionuclide transport on a site scale (500 m),
- to identify and characterize possible changes in groundwater chemistry caused by long-term drainage of a final repository.

### 4.4.3 Possible experimental design

The subject of investigation in this sub-project is a local fracture zone with an extent in excess of 200 m. The local fracture zone will be intersected by a number of smaller fractures and fracture zones, which means that a three-dimensional characterization must be done of the experimental volume. A suitable subject of investigation for this project is probably the system of permeable fracture zones with a north-northwesterly strike that was identified during the Äspö project's pre-investigation phase.

After the preliminary characterization, the experimental volume will be drained through a number of boreholes over an extended period of time. The chemical composition of the groundwater is measured in order to observe when superficial groundwater reaches the experimental level. This can provide an idea of whether or not fast transport channels exist between repository level and ground level.

The experimental volume consists of the volume inside the spiral above the second turn. This location is chosen in order to enable the rock volume to be investigated with boreholes from several different positions and with different directions. The experimental volume is situated at a depth of between 220 and 330 metres in order to reduce disturbances of groundwater chemistry at the laboratory's deeper levels.

Boreholes for characterization of the experimental volume are drilled at intervals along the spiral. For each side of the spiral, two or three boreholes are drilled. On the basis of data obtained, both a conceptual and a numerical groundwater model of the experimental volume are devised. The model is updated as data become available from following sides of the spiral. This will serve as an exercise in characterization in conjunction with the construction of a repository and how data are to be incorporated in models as they become available.

After the characterization of the rock volume has been concluded, packers are installed in the boreholes to isolate permeable fractures and fracture zones.

After the packer system has been installed, a number of subhorizontal and parallel boreholes are drilled in the bottom of the experimental volume. These boreholes will be drained over a long period of time (possibly the entire life of the Äspö Hard Rock Laboratory).

In this phase, a long-term monitoring programme is initiated for groundwater chemistry. Water samples are taken regularly from the drainage holes and from the packered-off sections in the characterization boreholes. This is done to study the long-term effects of repository drainage on groundwater chemistry. Data are expected on groundwater mixing due to altered flow paths, transport of surface water to repository level and changes caused by hydraulic testing, tracer tests and injection of grout.

The flow in the borehole sections is measured by means of dilution technique. Tracers are then injected both in possible fracture zones and in the surrounding "good" rock. Tracers can also be injected in one of the boreholes drilled from the surface. The tracer concentration is measured both in the drainage boreholes and in selected sections of the characterization boreholes. This experiment thus provides data on transport parameters representative of distances of several hundred metres if the surface boreholes are used for injection.

## 4.5 TESTS IN REGIONAL FRACTURE ZONES

### 4.5.1 Background

Siting of a future deep repository may take place in a rock slab surrounded by major regional fracture zones. These zones are often presumed to constitute the dominant transport pathways from repository depth to the biosphere. Since the water flow in these zones can be expected to be large, the zones probably bring about a substantial dilution of any radionuclides. The regional zones are probably also of importance for the stability of the repository in a long-term perspective, since future tectonic movements will primarily take place in the major fracture zones.

### 4.5.2 Goals

The goal of this project is to obtain data for validating models for flow and transport in regional and subregional fracture zones. Important aspects are:

- retardation and dilution of radionuclides in major fracture zones,
- the function of the regional fracture zones as boundary conditions for a deep repository,
- estimate the heterogeneity of flow within regional fracture zones, and
- estimate possible tectonic movements in the zone in a long-term perspective.

### 4.5.3 Possible experimental design

The subjects of investigation for this sub-project are the fracture zones NE-1 and EW-3 that were identified during the Äspö project's pre-investigation phase. NE-1 is a very transmissive regional fracture zone situated south of Äspö. NE-1 strikes in a northeasterly direction and dips approximately $60^{\circ}$ to the northwest. This means that the zone comes closer to the spiral with increasing depth. EW-3 is a local fracture zone that intersects Äspö. It strikes east-west and dips more or less vertically, intersecting NE-1 at a depth of several hundred metres.

Preliminary characterization of these zones is carried out as a part of the construction phase activities on passage of the zones with the access tunnel. This characterization is based primarily on short boreholes from the tunnel and measurements in these holes.

A more detailed characterization of the zones is conducted within the framework of this project via long boreholes drilled from the ground surface, the spiral or the access tunnel. Hydraulic and seismic cross-hole measurements as well as radar surveys are made in these boreholes. Special emphasis is placed on the correlation of geophysical and hydraulic data in order to ascertain to what extent geophysical data from a few boreholes can be used for characterization of the hydraulic heterogeneity of major zones.

All boreholes are equipped with a packer system that permits pressure recording and injection/extraction of tracers at different pressure and in several sections per borehole. Tracers are injected in selected boreholes, while the tracer concentration is measured in the other boreholes.

# 4.6 RADIONUCLIDE RETENTION

## 4.6.1 Background

Laboratory investigations for validating models and checking the constants used to describe radionuclide dissolution in groundwater, the influence of radiolysis, fuel corrosion, sorption on mineral surfaces, diffusion in the rock matrix and diffusion in backfill material have been conducted over a ten-year period.

It is, however, very difficult to simulate the following conditions accurately in a laboratory:

- Naturally reducing conditions.
- Natural concentration of colloidal particles
- Natural content of microbes
- Natural concentration of dissolved gases
- Undisturbed rock, i.e. rock with micropore systems and even major fractures that are not pressure-relieved by sampling.

All of these conditions are extremely important for the rock as a barrier, i.e. they have a great influence on the dissolution or retention of radionuclides if radioactive waste is exposed to groundwater.

Experience from Stripa and SFR also show that it is necessary to keep one part of an underground facility with constant access to groundwater, fractures and fracture zones accessible for migration experiments, geochemical sampling and material sampling over a long period of time. The experimental station should therefore remain operational for at least five years or as long as the facility is kept open.

## 4.6.2 Goals

The goals of the investigations are to:

- test dissolution and migration of radionuclides in situ,
- validate models and check constants used to describe the dissolution of radionuclides in groundwater, the influence of radiolysis, fuel corrosion, sorption on mineral surfaces, diffusion in the rock matrix, diffusion in backfill material, transport out of a defective canister and transport in an individual rock fracture,
- specially test the influence of naturally reducing conditions on solubility and sorption of radionuclides,
- test the ability of the groundwater to take up and transport radionuclides with natural colloids, humic substances and fulvic acids,
- investigate the influence of bacteria on chemical conditions and radionuclide migration, and
- investigate the chemical influence of grouting and backfill materials such as bentonite and cement.

### 4.6.3 Experimental design

**Preparations**

The development of the CHEMLAB probe has been commenced. The part of the probe where the tests are performed and samples collected is being designed in cooperation with the French CEA. CHEMLAB has been developed from the French probe FORALAB. The part that measures water composition already exists (CHEMMAC).

The experiments that will be performed in the probe out in the fracture zone are being prepared by means of laboratory tests. In connection with the laboratory tests, test set-ups are being developed that can be moved into the probe and connected to it. Planning and development have come the farthest with regard to diffusion tests, migration in a rock fracture and radiolysis. Both equipment tests and preparatory experiments will be carried out. New materials are being tested with the intention of using them in the probe.

Plans are being made for the rebuilding of the mobile field lab so that it can handle radionuclides. Similarly, cooperation is being discussed with the laboratory at CLAB on Simpevarp. They are well equipped to take care of a large portion of the activities in connection with handling of the probe, sample handling and analysis.

The entire chain for handling of radioactive tracers and samples is being analyzed, along with limits for the quantities of radionuclides that are needed, etc. Equipment for transport is needed, and there may also be a need for an additional unit beyond the probe, the mobile field lab and CLAB.

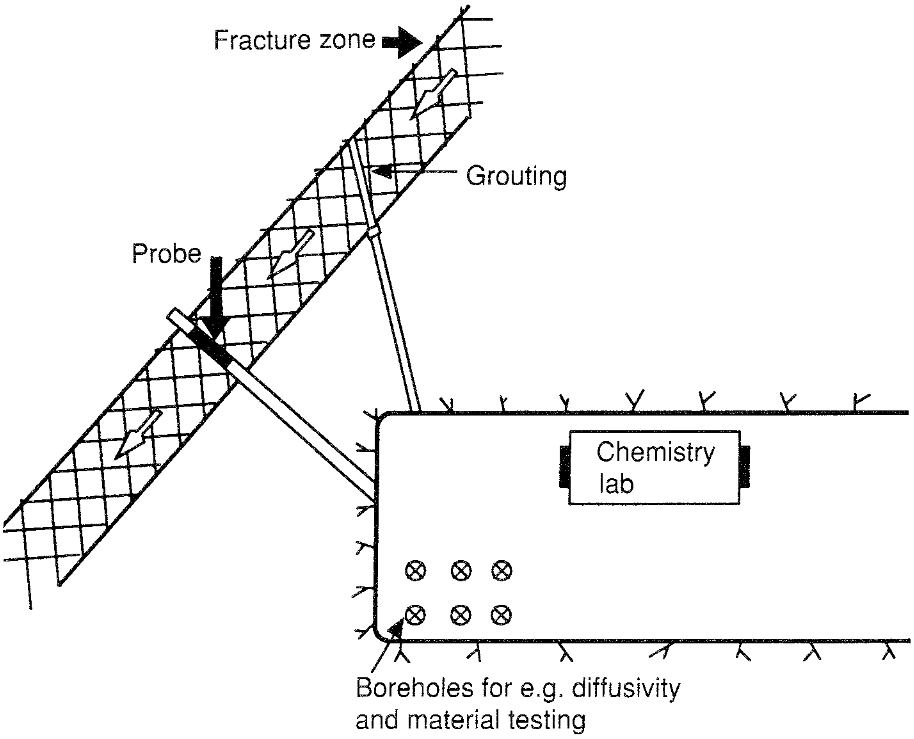

*Figure 4-1. Schematic design of radionuclide retention experiment.*

## Experiments performed in the Äspö Hard Rock Laboratory

A portion of the facility is being set aside for the execution of the experiments that have to be conducted over a long period of time. These tests require a water-bearing zone that can provide deep, undisturbed groundwater over a long period of time, see Figure 4-1. For this reason, a place far down in the Äspö Hard Rock Laboratory should be chosen. The basic idea is to utilize one of the minor zones that has been characterized within the framework of the project "Tests on block scale", see section 4.3. The experimental area shall be sufficiently large to accommodate a chemistry laboratory. A mobile field lab can be used. It shall then be slightly differently equipped than for water sampling alone. It shall be possible to characterize the redox properties of the water, i.e. there shall be redox analysis equipment, but it is not necessary to have ion-exchange chromatography equipment or other analysis equipment. The laboratory shall, however, have equipment for handling and analysis of radionuclides.

The CHEMLAB probe, which is being developed in cooperation with CEA of France, is used for tests inside the water-bearing zone. The CHEMLAB probe consists of two parts. One part is the geochemical probe that measures pH, Eh, conductivity etc. The other part is an automatic chemical laboratory where a number of different experiments can be performed. No water from the probe goes to the rock, which means that radionuclides can be used in the probe. Groundwater is also conducted from the zone into the underground chemistry laboratory for further experiments. The following experiments are performed in the probe, the laboratory and the fracture zone.

### *Experiments in the probe*

A series of experiments has been proposed. The list is so far provisional, but it serves as guidance for the design of CHEMLAB, procurement of peripheral equipment, preparation of permits to handle small amounts of radionuclides, etc. At present the list includes the following:

- Reduction of technetium and neptunium.
- Migration from buffer to rock.
- Radiolysis and radionuclide diffusion.
- Radionuclide sorption.
- Radionuclide solubility.
- Fuel dissolution.
- Colloid test.
- Microbe experiment.

The three first tests have been developed the farthest. The rock fractures needed for the tests are contained in drill cores, i.e. overcored fractures that are then installed in the probe. Oedometers and radiolysis cells are being developed and designed in resistant, chemically inert materials. Pumps, filters, couplings, hoses, valves etc. that are included in the probe and will be connected to the tests are defined on the basis of the experiment planning.

### *Experiments in chemical lab*

Such experiments are done as a complement to the experiments in the probe, i.e.

- repetition of the tests as a check,
- analysis of colloids, microbes, humic and fulvic acids, as well as tests of the ability of these aggregates to take up and transport radionuclides by means of suitable techniques.

*Experiments out in the fracture zone and the rock*

Supplementary tests can also be performed out in the fracture zone or in the rock outside the zone. The same area, laboratory equipment and existing holes into the zone can be used. One or more additional boreholes are also needed.

The supplementary experiments are planned to be performed only after the results from equivalent tests in the construction phase become available, see the redox tests described in section 4.7.

The following tests can be performed:

- Co–precipitation test with uranium and actinide analogues.
- Test with formation of colloids and transport with precipitated colloids.

In-diffusion of sorbing nuclides into the micropores in the rock is tested by injecting sorbing inactive isotopes, i.e. inactive caesium and strontium, together with non-sorbing tracers in undisturbed parts of the rock.

*Miscellaneous*

The same area and the chemistry laboratory can also be used for long-term tests of materials and material combinations. Examples of materials and material combinations of interest are: copper, iron, bentonite, concrete, uranium dioxide, concrete-bentonite, iron-bentonite, uranium dioxide-bentonite. The goal of the materials testing in situ is to validate models for corrosion and other changes, as well as the interaction between different materials. It is of particular interest to investigate the chemical change in water composition brought about by backfill material and injection grout.

## 4.7 REDOX REACTIONS

### 4.7.1 Background

The data obtained within the SKB investigations show that the groundwater is reducing wherever it is sampled in the bedrock. The shallow samplings derive from a depth of 40-50 m, the deepest from more than 1000 m. In all, 82 levels in 25 different cored holes have been sampled since 1982. Its buffering capacity is low, however, especially in water with a high pH and associated low solubility for bivalent iron. On the other hand there is a very high buffering capacity in the different reducing minerals that occur. It is very easy to convince oneself that only a fraction of the redox buffering capacity of the rock is needed to resist every conceivable oxidative attack from oxygenated water that penetrates down during the time a final repository is open and from an oxidizing front caused by radiolysis of water in contact with the spent fuel.

Even if the rock's redox buffering capacity is more than sufficient on the whole, it is conceivable that the redox conditions could change in a channel that leads water into the repository while it is open. After sealing of the repository, this channel constitutes a rapid transport pathway for radionuclides up to the biosphere. In such a situation, it is possible that materials that have been oxidized by radiolysis could migrate all the way up to the biosphere without reduction and sorption of the radionuclides. The consequences of this are the same as of the scenario in KBS-3 where oxidizing conditions have been assumed in the geosphere, i.e. the individual dose is 100 times higher than under otherwise identical but reducing conditions.

The purpose of the redox experiment is to investigate parameters that are of importance for the propagation of the redox front in the rock. Two such parameters are channelling and "flow-wetted surface area". Besides oxygen reduction, it is important to know how redox-sensitive nuclides are affected by different redox reactions, such as uranium reduction, colloid formation and co-precipitation.

The impact of microbes, which are an important cause of geochemical changes, is also being studied within the framework of the redox experiment. Investigations carried out to date show that bacteria are present in all groundwater that has been sampled. This may possibly be due to contamination during drilling and other events preceding sampling. The purpose of the project is to answer the following questions:

- Are bacteria present in undisturbed rock?
- If so, which species dominate?
- How large a fraction of the bacteria are on fracture surfaces?
- What do they live on?
- Which are active?
- Do they produce complexing agents?

### 4.7.2 Goals

The goal of the redox experiment is to clarify how quickly oxygen reduction takes place in a water-bearing fracture zone and to ascertain the effects of the penetration of a fracture system that has previously been reducing by an oxidizing front. The effects on both water and mineral composition will be studied. The mechanisms behind the processes will be examined so that the results can be applied generally to nuclide transport calculations. The dependence of sorption mechanisms on the flow-wetted surface area will in particular be explored. Another goal is to determine the presence of bacteria and their influence on groundwater chemistry.

### 4.7.3 Experimental design

**Ongoing investigations**

The block-scale redox experiment was begun in 1991. The experiment is being conducted in a side tunnel at the 510 m section in the access tunnel to the Äspö Hard Rock Laboratory. Changes in the character of the water and the fracture minerals are being studied via three short cored holes that penetrate a water-bearing zone.

The redox experiment can be divided into three parts.

Part 1: A thorough characterization of the water chemistry is carried out. The main components, tracers and isotopes are determined. At the same time, the drill core is sampled and analyzed with regard to isotopes, mineral composition, chemical composition etc. The breakthrough of the redox front is monitored.
After the redox front has broken through, the water's content of particle-bound material will be analyzed regularly. The total quantity of particle-bound material and the proportions of different elements will be determined.

Part 2: Some time after the redox front has broken through, an overcoring of the holes is done and an analysis of both water and drill core is repeated. In this analysis round especially, the work will be concentrated on clear changes caused by the fact that oxygenated water has run in the fracture system, e.g. changes in the iron minerals.

Part 3: The results of completed analyses and interpretations are evaluated.

Part 1 of the project is currently under way and instrumentation has been installed to monitor the breakthrough of the redox front. Data from the initial phase of the experiment have been compiled in Progress Report 25-92-04. A preliminary interpretation of the results shows that:

- Surface water and oxygen breakthrough took place very soon after the tunnel penetrated the zone. The breakthrough time lies within the expected span, but at the very shortest extreme.
- The occurrence of surface water and oxygen breakthrough has, on the other hand, not been confirmed in the three boreholes from the tunnel. Mixing calculations show, however, that of the water that has been drained from the boreholes, 50% is surface water and 50% saline water that was present in the zone before the tunnel broke through.
- The fresh water near the surface of the ground in the zone is reducing and sometimes contains high iron contents. The variations in water chemistry also show that the flow is to some extent channelled to the different boreholes.

The next stage entails getting surface water down into the three holes drilled through the zone and characterizing chemical changes in the water chemistry, dissolved constituents and particle fractions.

During the monitoring phase, the hydraulic conditions around the zone will be further clarified if possible. Tracer tests will then be performed for the purpose of ascertaining the complex flow pattern in the zone. Dye tracers will be injected in two percussion boreholes from the ground surface that enter the zone at depths of 15 and 40 metres, respectively. Drainage will take place through two of the boreholes from the drift, one at a time. If the redox breakthrough occurs during the monitoring phase, the design of the tracer test will be reconsidered.

After the tracer test has been evaluated, the flows are optimized so that oxygenated water breaks through. A considerable increase in particle content is expected with the redox front.

In connection with the groundwater sampling, the presence and activity of bacteria in the groundwater are studied.

### Planned investigations for the operating phase

The block-scale redox test described above is qualitatively complete. However, it will be difficult to determine the redox buffering capacity in the flow paths since the minerals, the ratio between mineral surface area and volume, and the flow velocities cannot be determined explicitly. A similar test must therefore be carried out on a smaller scale, where all parameters can be checked. Besides studying oxygen reduction alone, it is also possible to study on a small scale how other redox-sensitive nuclides – chiefly uranium, but also actinide analogues – are affected by the redox front.

The availability of iron and sulphide-containing minerals is of the utmost importance for whether fracture surfaces can react with redox-sensitive actinides and uranium. Besides pure redox reactions, sorption and co-precipitation mechanisms can also contribute to fixing these nuclides. The sorption reactions are probably irreversible.

Redox reactions and sorption will – if possible – be studied in the fracture or fracture zone previously characterized for the block-scale redox test. The results will also be used for the purpose of defining the flow-wetted surface area.

*Possible experimental design*

Uranium(VI) solution will be injected continuously via boreholes in the zone/fracture until breakthrough is observed in another borehole. This will have been preceded by the characterization of the flow by means of tracer tests. After injection has been interrupted, new holes will be drilled in the zone and the core will be analyzed with respect to uranium coating of the fractures.

The migration of the redox front and co-precipitation reactions and colloid formations will be studied by overcoring of parts of the zone.

Finally, oxygenated water will be injected to compare the redox kinetics of the oxygen reduction with the redox kinetics of the uranium reduction. In this way the results of the large-scale redox test can be related to uranium reduction in the flow paths.

The measurement results are evaluated to determine the reaction rate of the identified reactions.

In order that local variations can be taken into account, the test must be performed at a minimum of two different places.

*Preparatory work*

Some laboratory tests with the same thrust as the field test will have to be performed in conjunction with the planning of the test. Parts of the preparatory work coincide with the block-scale redox experiment. The other investigations that have to be conducted in the lab are as follows:

- Reduction of oxygen in contact with minerals. Such investigations are required in order to be able to determine the scale of the field tests. Flow velocity and mineral surface area are of the greatest importance. Such tests can be based on experience from previous tests done, for example, at the department of inorganic chemistry at KTH (the Royal Institute of Technology, Stockholm).
- Reduction of hexavalent uranium in contact with minerals. The purposes of the tests are the same as for reduction of oxygen.

The redox buffering capacity of the rock determines how many injections can be made in each zone. It is therefore necessary to know the capacity as a function of the contact time. This is strongly linked to the flow-wetted surface area.

## 4.8 DISTURBED ZONE AROUND DRIFTS

### 4.8.1 Background

The making of holes in the rock – whether they be in the form of drifts, shafts, deposition holes or boreholes – entails a disturbance of the rock surrounding the hole in relation to the conditions that existed before the hole was made. The impact on the surrounding rock depends on such factors as the hole-making method, the size of the hole, stress conditions, the structure of the rock type and the presence of fractures. The term "disturbed zone" is often used in this context. This refers to the zone around the hole where the properties of the rock have been altered in some respect due to the existence of the hole or as a consequence of the work (e.g. blasting) that has been carried out to create the hole.

The properties and extent of the disturbed zone must be taken into account in the design of the repository and in the assessment of its long-term safety. To determine the extent to which the disturbed zone affects the long-term safety of a deep repository, it is necessary to understand the processes that affect the properties and extent of the disturbed zone.

The disturbed zone around a drift or a deposition hole causes a change in the hydraulic properties of the rock. An increase in the axial hydraulic conductivity along a tunnel would mean that the disturbed zone constituted a potential water conductor and transport pathway for radionuclides. A change (increase or decrease) in the radial conductivity (often called “skin”) above all affects the characterization of the hydraulic properties of the undisturbed rock. The skin effect causes the inflow to tunnels to be greater or less than it should really be, which must be taken into account when tunnel data are used for validation of models. The disturbed zone also entails a change in the mechanical properties of the rock, which can affect the stability of drifts and rock caverns. The mechanical and hydraulic properties of the disturbed zone are also of importance for the description of how water saturation and homogenization take place in the buffer material (bentonite) surrounding the canister.

The properties and behaviour of the disturbed zone have been studied in situ at a number of underground research laboratories during the past few decades. The research work that has the greatest relevance for the Swedish programme is the work that has been done in the Strip Mine since 1977, the Underground Research Laboratory (URL) in Canada, the Grimsel Test site (GTS) in Switzerland and at several laboratories in the USA, see e.g. SKN Report 59. In 1991 a test was conducted in the Äspö Hard Rock Laboratory’s access tunnel where the extent and character of blasting damages were studied as a function of different blasting plans, see Progress Report 25-91-12--16.

The experiments that have been carried out to date have identified a number of mechanisms that are evidently of importance for the properties of the disturbed zone. The mechanisms that have been judged to be potentially important are:

- The initial stress load that is obtained at blasting and passage of the drift front.
- New fractures created by blasting.
- Stress redistribution and rock movements caused by the cavity created by excavation of the drift.
- Two-phase flow caused by ventilation (drying), degassing of gases dissolved in the groundwater and/or intrusion of blasting gases.
- Chemical reactions and mineralogical changes in the tunnel’s near field (can be caused by mechanical impact, blasting gases, oxygen intrusion, mixing of groundwaters with different chemistry, and/or bacterial activity).
- Impact on the rock caused by buffer material (e.g. swelling pressure, intrusion of bentonite in fractures).
- Thermal impact on the rock due to the heat from the waste canister.
- Creep effects in the rock caused by stress relief and its impact on the long-term mechanical stability and the hydraulic properties of deposition tunnels.

Even though several potentially important processes have been identified, the relative importance of the different processes for nuclide transport in the disturbed zone is relatively poorly known. This can be attributed to the fact that several coupled processes influence the properties of the rock. Another problem is the lack of measurement techniques suitable for quantifying the properties of the disturbed zone.

### 4.8.2 Goals

The general goals of the investigations of the disturbed zone are:

- to quantify the parameters that control processes in the disturbed zone and to shed light on the relative importance of the processes for the performance of the repository system, and
- to develop and validate quantitative models for essential processes in the disturbed zone.

### 4.8.3 Possible experimental design

The disturbed zone constitutes a large problem complex where a number of processes interact in a complex fashion. To be able to describe the different processes and experimentally verify quantitative relationships, it is important to separate different processes to as great an extent as possible and study each one independently. The research on the disturbed zone has therefore been divided into a number of sub-projects.

First the influence of degassing and two-phase flow will be studied via measurements in several holes drilled especially for the purpose. Degassing and two-phase flow are processes that are dependent on the water pressure and are in principle independent of the existence of a drift. These processes can be studied to advantage in boreholes, where the influence of changes in rock stresses can be minimized. The results from the borehole experiments can then be used to estimate the influence of two-phase flow around a drift.

In a later phase a more comprehensive experiment will be conducted where the hydraulic and mechanical properties of the rock mass are studied in conjunction with the drilling of a simulated deposition drift. This project is designed in detail against the background of the experience gained from previous experiments.

Only when additional knowledge has been obtained on the mechanical and hydraulic changes around a bored drift can there be reason to design and carry out an experiment to study the impact of blasting. In accordance with plans presented here, such investigations lie so far ahead in time that no reason can be found today to prepare a description for such an experiment.

### 4.8.4 Degassing of groundwater and two-phase flow

**Background**

In the experiments that were carried out within the framework of the Site Characterization and Validation project in Stripa, degassing of groundwater was identified as a potentially important process in the disturbed zone. The gases dissolved in the groundwater go out of solution and form bubbles at low pressures. In this way a zone will be created around the drift that is not completely water-saturated. The unsaturated zone can then grow due to drying-out of the rock caused by ventilation. Unsaturated conditions mean that two-phase flow of gas and water can occur in the vicinity of a drained borehole or a drift, leading to a reduction of the hydraulic conductivity. This process is expected to reduce the inflow to drifts during the construction of a deep repository, but since the water pressure returns to normal when the repository is backfilled, two-phase flow is not expected to play any role for the long-term performance of the repository.

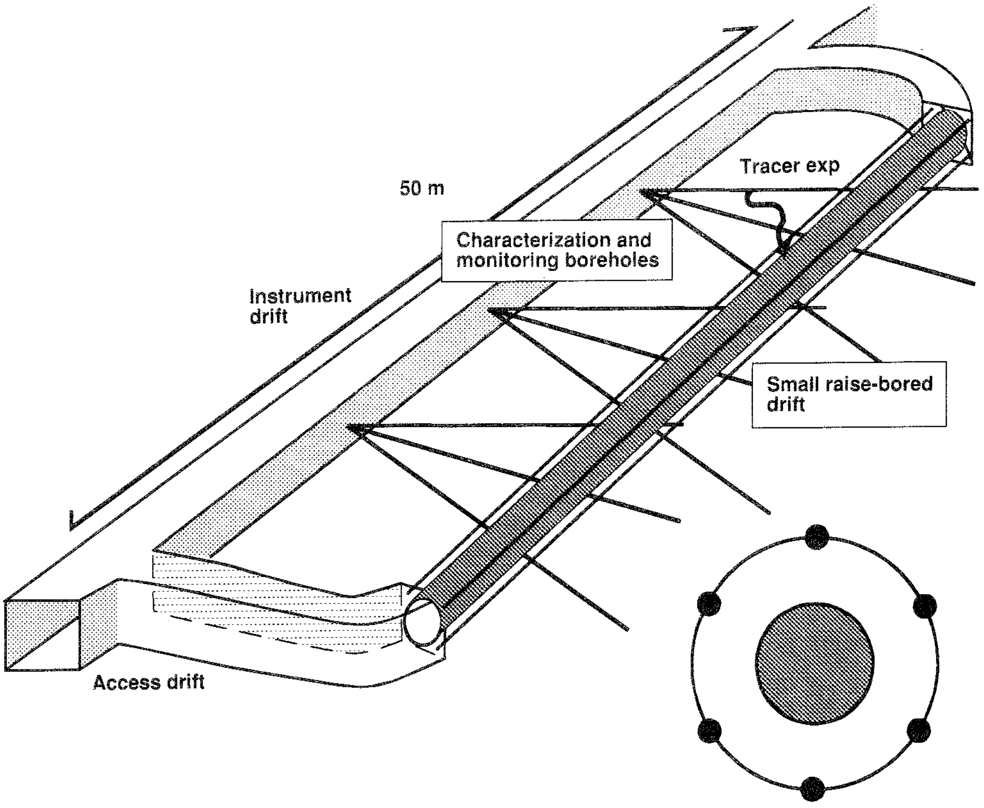

*Figure 4-2. Potential layout for a tunnel effect investigation.*

### Goals

The goal of this sub-project is:

- to build up a fundamental understanding of and quantitatively describe degassing of groundwater and its effect on the hydraulic properties of the rock and possibly hysteresis effects in conjunction with the restoration of water-saturated conditions.

### Experimental design

The study of two-phase flow and its importance in the disturbed zone is begun with a review of the literature. This is followed by laboratory experiments where degassing of groundwater and its effect on groundwater flow through fractures is simulated. Development of theoretical models is initiated and runs parallel to the laboratory tests.

In-situ tests are conducted where the groundwater flow to a number of horizontal boreholes is measured under a gradual reduction of the water pressure. Non-linear relationships between flow and pressure will be an indication of degassing and resultant two-phase flow. The groundwater will be tested at regular intervals to determine gas content and chemical composition. The water chemistry is investigated to check that drainage of the boreholes does not give rise to mixing of different groundwater types and thereby possibly precipitation of calcite.

The boreholes are then emptied of water and invaded with air. The boreholes are subsequently filled with water and the pressure is gradually increased. The hydraulic properties of the rock are measured to study hysteresis effects as water-saturated conditions are restored in the rock.

### 4.8.5 Tunnel effects

**Background**

After the introductory studies of the effects of two-phase flow, the necessary information will be available to carry out a larger integrated study of the disturbed zone in a bored drift. The test is set up so that a direct comparison is obtained between the hydraulic properties before and after the creation of the drift.

**Goals**

The goals of the sub-project are:

- to quantitatively describe mechanical processes in the disturbed zone around a bored tunnel and their effects on the hydraulic properties of the rock,
- to study the effect of geological structures and stress fields on the hydraulic and mechanical properties of the disturbed zone,
- to clarify to what extent observations in tunnels are representative of conditions in the undisturbed rock,
- to quantify mechanical and hydraulic effects in conjunction with water backfilling of a bored tunnel, and
- to characterize and prepare an experimental area that can be used for testing the interaction between rock and buffer material.

**Possible experimental design**

The in-situ tests of the disturbed zone are planned for a test area within the Äspö Hard Rock Laboratory. After the completion of the project, the experimental drift can be used to study different questions, such as the interaction between buffer material and rock and the difference between blasted and bored tunnels.

The tests will be performed along a 50 m long experimental drift. The drift is assumed to be parallel to and at a distance of about 30 m from an instrument drift. Boreholes for characterization of the rock within the experimental area and for installation of measurement equipment are drilled from the instrument drift. If possible, an instrument drift is also excavated above the experimental drift so that investigation holes with two approximately orthogonal directions are obtained. The experimental drift is reached through two access drifts, see Figure 4-2. The design of the test in its present form shall be regarded as a rough sketch of the project set-up. Detailed designing will be done on initiation of the project.

After an introductory characterization based on measurements in the boreholes from the instrument drift followed by instrumentation of these boreholes, a pilot borehole is drilled between the access drifts. The distribution of groundwater inflow to the pilot borehole is measured under different water pressures, while the water pressures are recorded in existing boreholes. Then a number of parallel boreholes are drilled in a circle around the pilot hole to create a "simulated drift". The inflow distribution to these boreholes is measured, while pressure changes are observed in other boreholes. Tracer tests are carried out between the boreholes from the instrument drift and the simulated drift to characterize the flow in a radial direction. Flow and transport in the axial direction along the boreholes are measured by means of tracer tests between packered-off sections in the borehole array.

Then a drift with a diameter of 1.7 or 2.4 m is bored. Water pressures, rock stresses and rock movements are measured during excavation of the drift. The drift is mapped and the results are compared with the mapping from the boreholes. After the drift has been completed, the water saturation of the rock is measured as a function of time and the distance from the drift wall. The inflow distribution to the drift is measured under different hydrostatic pressures. This is achieved by means of a mega-packer system that can be moved along the drift. The system will consist of several packers that divide the drift into several sections. Tracer tests are compared to quantify transport and flow in both the radial and the axial direction. A comparison of the results from the bored drift with those from the simulated drift should provide a quantification of the differences in the hydraulic properties of the disturbed zone that can be attributed to stress redistribution and rock movements etc.

## 4.9 MODELLING OF GROUNDWATER FLOW AND RADIONUCLIDE MIGRATION

### 4.9.1 Background

Numerical modelling of, for example, groundwater flow has been an integral part of the Äspö Hard Rock Laboratory from the very beginning. Originally, the modelling was begun with a simple generic modelling of different alternative designs of the laboratory, taking into account the saline groundwater that exists. Gradually the models were refined into a comprehensive prediction model of the access tunnel and its effects on groundwater levels and water flux. The access tunnel is currently under construction and the model is being tallied against data obtained during the construction phase.

Groundwater modelling will continue to be an important part of the Äspö Hard Rock Laboratory. Transport and flow modelling is currently under way for the purpose of refining the existing models and including solute transport in a more comprehensive fashion.

The processes that have been modelled so far within the Äspö project are mainly groundwater flow and, to some extent, transport of non-sorbing solutes. These processes will continue to be modelled, since a number of conceptual questions remain to be answered, such as how flow and transport take place in the disturbed zone around a tunnel, etc.

Transport of sorbing tracers (radionuclide migration) and movement of chemical fronts are next in line for numerical modelling within the framework of the Äspö project. The reason for this is naturally that most radionuclides are sorbing and that the movements of the saline front and the redox front are critical for the chemical stability of the deep repository.

For a deep repository, the investigation scale can be related to the transport distance in a near field, to an intermediate field of good rock in the vicinity of the final repository tunnels and a far field in the conductive fracture zones located further away. To achieve the goal of finalizing the design of and understanding the safety of a final repository, experiments and modelling on all three scales are necessary. This is reflected in the experimental programme, which includes experiments aimed at phenomena on all three scales.

### 4.9.2 Goals

The modelling ties in with the Äspö Hard Rock Laboratory's stage goal to refine and test on a large scale methods and models for describing groundwater flow and radionuclide migration.

The goals of the numerical modelling work within the Äspö project are:

- to understand and conceptualize groundwater flow and radionuclide migration in fractured rock,
- to predict the outcome of the different experiments with numerical models,
- to verify and validate used models,
- to transfer knowledge between organizations participating in the project,
- to compare and evaluate models in order to assess their suitability as a basis for licensing of a deep geological repository.

### 4.9.3 Experimental design

**General**

All of the major experiments that are intended to be carried out during the operating phase are preceded by predictions that are based on numerical modelling, or at least rough calculations. Each modelling should be evaluated in accordance with the principles that apply within the project. An example is that measured values shall be compared with predicted values with a complete review of the structure and the principles of the model. Evaluation of the models should be done by a task force.

The experiments that are intended to be modelled are described below. In addition, some of the investigations that have been carried out during the pre-investigation and construction phases will be modelled. The pumping and tracer test LPT2 will be utilized as an introductory modelling exercise for international participants in the Äspö Hard Rock Laboratory.

**The combined pumping and tracer test LPT2**

The pumping test LPT2 has been proposed as an introductory exercise for the participating modelling groups. This test took place on southern Äspö where the spiral tunnel will be built. The actual test is a two-month pumping test that was combined with a converging tracer test where a number of tracers were injected in different borehole sections around the pump hole. The tracers' points of entry into the pump hole were identified. The flow rate through the injection sections was determined by means of the dilution technique.

The goals of modelling the LPT2 test once again are:

- to furnish a well-defined test case for the new modelling groups who come into the Äspö project,
- to try different modelling methods.

The background data comprise a large number of calibration cases, on which the conceptual model and the predictions made before the construction began were based. For this exercise all data are available, from the first tests in the area up to and including the complete results from the LPT2 pumping test.

The following steps in the LPT2 exercise are recommended:

1) Calibration of a groundwater flow model of southern Äspö.
2) Modelling of natural groundwater conditions on southern Äspö.
3) Modelling of drawdowns during pumping test LPT1.
4) Modelling of drawdowns during pumping test LPT2.
5) Modelling of tracer transport during tracer test LPT2.

### Tests on detailed scale

The movements of sorbing tracers are only possible to follow on a small geometric scale during the life of the laboratory. The experiment with sorbing tracers will therefore be carried out in a borehole group where it is possible after the experiments have been concluded to blast out the rock to analyze the absorbed tracer on fracture surfaces.

Modelling will therefore be carried out on a fracture scale and the models will be calibrated against hydraulic tests and tracer tests in the borehole group. The following modelling steps are foreseen:

1) Conceptual model of transport of sorbing tracers. Laboratory tests and auxiliary models to understand and quantify the transport of sorbing tracers.
2) Flow and transport model for the borehole group. Calibration against data from hydraulic tests and tracer tests with non-sorbing tracers. Prediction of specific surface area.
3) Modelling of transport of sorbing tracers for defined fractures in the borehole group.

### Tests on block scale

The goal of this experiment is to investigate the flow distribution in an individual major fracture or a minor fracture zone of the kind that can be expected to intersect a final repository tunnel. The connection of this zone to the fracture system in the sound rock is also of interest. In this experiment it is possible to calibrate the models against radar tomograms from salt injection tests in the same plane as the groundwater conductor. The scale of this experiment should be such that it is for the most part only possible to conduct the experiment with non-sorbing or very weakly sorbing tracers.

The following modelling steps are foreseen:

1) Model of the groundwater flow in the water-bearing fracture zone.
2) Calibration of the flow model against radar tomograms.
3) Predictive modelling and calibration of some tests with sorbing tracers.

### Tests on site scale

The hydraulic connection between fracture networks and local fracture zones will be studied more closely on the site scale. The test volume will be situated inside the spiral tunnel system, which will also make it possible to drain this volume and test possible effects of the drainage. Of special interest are any redox changes caused by air entering the fracture system.

The experiment will start as a characterization of the experimental volume. The following modelling steps are proposed:

1) Flow and transport model of the test volume, calibration against characterization data, including hydraulic and tracer tests and seismic tomography.
2) Prediction of drainage of the test volume, including aeration and movements of the redox front.
3) Calibration and modification of the model on the basis of data from the drainage period.

### Tests in regional fracture systems

In most safety assessments, regional conductive fracture zones are the main conduits for groundwater transport from the final repository up to the biosphere. Immediately south of the test volume for the Äspö Hard Rock Laboratory, the access tunnel passes through a large regional zone of high transmissivity, NE-1. The characterization of this zone has been a principal task during the pre-investigations. The passage through the zone during the construction phase has not been without difficulties.

The test planning calls for utilizing NE-1 for an experiment aimed at characterizing flow and transport in regional fracture zones.

Important parts of the modelling work will be to utilize data from the cross-hole tests for hydraulics, seismics and radar. The following modelling steps are expected:

1) Setting-up of a global flow and transport model for NE-1 based on available data. Prediction of selected tests in the experimental programme.
2) Calibration of the model against test results and cross-hole test data. Prediction of tracer tests.
3) Revision of model based on tracer test data.

### Redox reactions

The experimental programme outlined above contains several hydrochemical questions. During detailed planning of the programme, further integration of questions relating to groundwater flow and hydrochemistry will be done. These questions include e.g. the mobility of radionuclides, the importance of channelling and specific surface area, and changes in redox conditions caused by oxygen entering the system.

The modelling exercise steps are:

1) Conceptual model of movements of the redox front.
2) Flow and transport model for the test areas.
3) Modelling of the movement of the redox front.
4) Revision of model on the basis of experimental data, evaluation of conceptual model.

### Modelling of the disturbed zone around the tunnel

It is a well-known fact that the blasting-out of a tunnel in fractured, crystalline bedrock affects the hydraulic properties of the rock immediately outside the tunnel wall. Some of the causes identified for the disturbed zone are: redistribution of stresses, blasting damages, chemical reactions and two-phase flow phenomena due to drying-out and degassing of the groundwater. The consequences of the combination of these phenomena and perhaps a few others are still poorly known. Experiments in the disturbed zone will be conducted in order to understand and explain these phenomena and to see whether they persist when the final repository is backfilled.

Only the guidelines for the modelling programme are given here:

1) Conceptual model for two-phase phenomena. Laboratory experiments and numerical modelling of degassing and bubble movements in fractured rock.
2) Calculations of inflow to pilot borehole.
3) Predictive modelling of simulated drift inflows.
4) Modelling of inflow to bored tunnel.
5) Simulation of backfilled tunnel.

# 5 DEMONSTRATION OF CONSTRUCTION AND HANDLING METHODS

## 5.1 BACKGROUND

A deep repository consists of a large number of parts that are identical to each other. A KBS-3 repository, for example, consists of several thousand canisters, each of which is surrounded by highly compacted bentonite in a deposition hole. The different components (fuel, canister, clay, rock) combine to achieve a safe disposal. Other important components are e.g. sealing plugs for shafts, boreholes or tunnels, grouting shields for diversion of mobile groundwater and tunnel fill. All of these parts must be executed with a certain minimum quality in order for the repository in its entirety to meet the safety requirements. When applying for a building permit, it is urgent to demonstrate that this minimum quality can be upheld. During pre-investigations and detailed characterization, a gradual increase in the level of detail of the description takes place. This description and understanding is deepened during the construction of the repository. It is important to demonstrate how data will be gathered and analyzed during the repository's construction phase. Before construction of the repository takes place, it is also possible to demonstrate different methods for making tunnels and deposition holes, for example drilling/blasting or full-face boring. The laboratory also provides an opportunity to test which measurements and analyses are to be done before choosing the rock volumes in which the waste is to be placed. It is also possible – for example in conjunction with full-scale tests – to develop and test methods for quality control and quality assurance in the execution of different parts of the deep repository system.

## 5.2 POSSIBLE DEVELOPMENT WORK

Detailed planning of the development work will take place after the final selection of a repository concept.

### Methodology for selection of location of repository tunnels and canister positions

The "design-as-you-go" philosophy that is being tried during the construction phase, stage 2, is being refined and applied within a "repository area" where certain components in the repository (buffer-rock) can later be demonstrated.

The development work concerns e.g. strategy for characterization of the near field, demonstration of how characterization is carried out, showing how flexibility can be achieved, i.e. adaptation of deposition tunnels and canister holes to the properties of the rock.

Another purpose of the investigation is to characterize the rock volume where tests of repository components will later take place, see below.

### Grouting and sealing of water-bearing zones

Development work concerning grouting is being done during the construction phase at Äspö. This work can be continued during the operating phase. Further tests and demonstrations are only needed with regard to the passage of water-bearing fracture zones.

### Testing of machinery

The development of machinery proceeds according to the following steps:

1) Conceptual design of full-sized units.
2) Building and testing of units on a model scale.
3) Building of a full-sized prototype.
4) Testing of the prototype.
5) Modifications.

Testing of the equipment, i.e. step 4, is done in the Äspö Hard Rock Laboratory.

Current prototypes include a unit for emplacement of the bentonite in a canister hole or drift, a unit for deposition of the canister, a unit for flushing-out or drilling-out of the bentonite (retrieval) and a unit for retrieval of the canister.

### Testing of deposition

Testing in the Äspö Hard Rock Laboratory is focussed on depositing canisters with the right weight and weight distribution. Bentonite blocks with the intended moisture content and weight are used. A number of deposition positions are needed in order for the sequence to be able to be simulated realistically.

When the number of positions has been filled, the test canisters can be retrieved and a new sequence carried out. This means that the following requirements are made on the testing area:

- Realistic rock conditions with fracture zones and repaired stretches to the extent that could be managed in the deposition, plus also poorer conditions to provide information on practical limits.
- Water conditions that both describe realistic conditions and represent overly wet conditions (practical limits).

Eventually it will be time to test the recovery equipment as well. In this case, however, only one unit of each kind will be developed. The prototypes will be tested in the Äspö Hard Rock Laboratory.

### Testing of backfilling with bentonite/sand mixtures

Regardless of the repository concept, certain drifts, blasted-out areas and shafts will be backfilled with bentonite/sand mixtures. In the KBS-3 concept, however, such backfilling is included as a part of the deposition process, while it is not required in "horizontal deposition" until the final phase, at sealing.

In KBS-3 it is important that the upper part of the drift can also be filled with highly impervious material (to prevent the bentonite in the canister hole from swelling upward, and prevent rock creep downward in the roof of the drift.) Spraying with the shotcrete technique alone is not enough. The method must be refined and equipment developed. Long-term tests can eventually show whether sufficiently good swelling properties have been obtained.

### Testing of plugging of drifts

In the case with "horizontal deposition", for example, each deposition drift shall be sealed with a plug. Development of the machinery is not as important as the method itself, and assurance of its long-term performance. However, equipment must be available at an early stage, since the long-term tests have to start early in the programme.

# 6 TESTING OF IMPORTANT PARTS OF THE REPOSITORY SYSTEM

## 6.1 BACKGROUND

In a well-characterized rock mass, it is possible to carry out full-scale tests with parts of the selected repository concept. These tests may have to be commenced in the mid-90s and proceed for a long time. Tests can be performed on individual components in the repository system. The hydraulic interconnection between rock and buffer can be analyzed. The impact of e.g. temperature variations can be evaluated. Before a permit for sealing of the facility is issued, a demonstration can be made of how sealing of the facility is to be carried out. The results of these tests can provide support for the various permit applications. They are also expected to contribute towards increased confidence in and acceptance of the selected concept.

## 6.2 POSSIBLE DEVELOPMENT WORK

An important part of the repository system, which can be studied in the Äspö Hard Rock Laboratory, is the performance of the bentonite buffer and its interaction with the rock in the near field.

This can be done, for example, in an equivalent of the Buffer Mass Test in the Stripa project, where thermally induced effects are simulated by means of artificial heating. The homogenization of the buffer and the hydraulic regime in the near field can be studied. During a ten-year period, a temperature maximum is reached in the interface between canister and bentonite. A question related to this problem complex is the plugging of deposition drifts. In the "horizontal deposition" concept it is natural to terminate the deposition drift with a plug, whose long-term performance can also be observed.

Other tests can also be performed with regard to migration of nuclides and gas through the buffer and temperature-induced movements of canisters and the near-field rock.

Examples of tests than may be performed are commented on briefly below.

### Buffer tests

Tests are performed to further clarify the behaviour of the buffer and its interaction with the near-field rock. The tests are based on those conditions that can be expected to exist in the deep repository and those that exist on the testing site. The experiments are ultimately concerned with the buffer's protection of the canister against movements in the rock and its resistance to the transport of radionuclides from a failed canister to the surrounding rock. To start with, the near field around a test drift is characterized. This is followed by instrumentation, backfilling with buffer material and plugging. Essential parameters such as temperature conditions, moisture content, pressure build-up and mechanical movements can then be studied over a number of years.

### Bentonite alteration

The impact of sulphide, potassium and chloride ions and corrosion products on the bentonite can be studied. The purpose of the experiments is to determine changes in the swelling properties and hydraulic conductivity of the bentonite.

### Migration of radionuclides in bentonite

The bentonite's $K_d$ values for different nuclides have been determined in the laboratory on limited sample quantities. Field tests can shed light on the importance of the scale effect.

### Gas migration

Depending on the choice of canister design, it is possible to study the processes of hydrogen gas migration from a failed composite canister.

### Plugging

The plugs in a deep repository have special functions depending on where they are placed. Those that seal off the deposition drifts shall resist the entire swelling pressure of the bentonite so that the volume of the buffer does not increase. Nor may the pressure on the plug create openings for water transports either through the plug, in the contact between the plug and the rock, or in the near-field rock. At the Äspö Hard Rock Laboratory, function tests can be performed on those plugs that are needed for other experiments.

# 7 SCHEDULE FOR THE OPERATING PHASE

The research, development and demonstration work presented in the preceding chapters is designed to meet the needs that can be foreseen today. The experimental programme currently being planned extends over a fifteen-year period. It is then natural that the experiments should be ranked in order of priority so that they can be scheduled according to when the knowledge and in-situ data are needed and when practical opportunities exist to perform the experiments.

The RD&D activities scheduled for the next few years can be regarded as being well founded and defined. Activities further ahead in time are more sketchily described.

The following judgements and priorities have been made in drawing up the overall schedule for the operating phase of the Äspö Hard Rock Laboratory:

The projects **Tests on detailed scale** and **Tests on block scale** are being scheduled early. The purpose of these projects is to obtain in-situ data on essential parameters for radionuclide migration and development and validation of models. The chances of obtaining good results are deemed to be greatest on the detailed and block scales, so experiments will be performed on these scales to begin with. Pilot studies aimed at studying the transport of sorbing tracers in individual fractures (detailed scale) will be initiated even before construction of the Äspö Hard Rock Laboratory has been finished. Larger-scale experiments will be performed in a later phase.

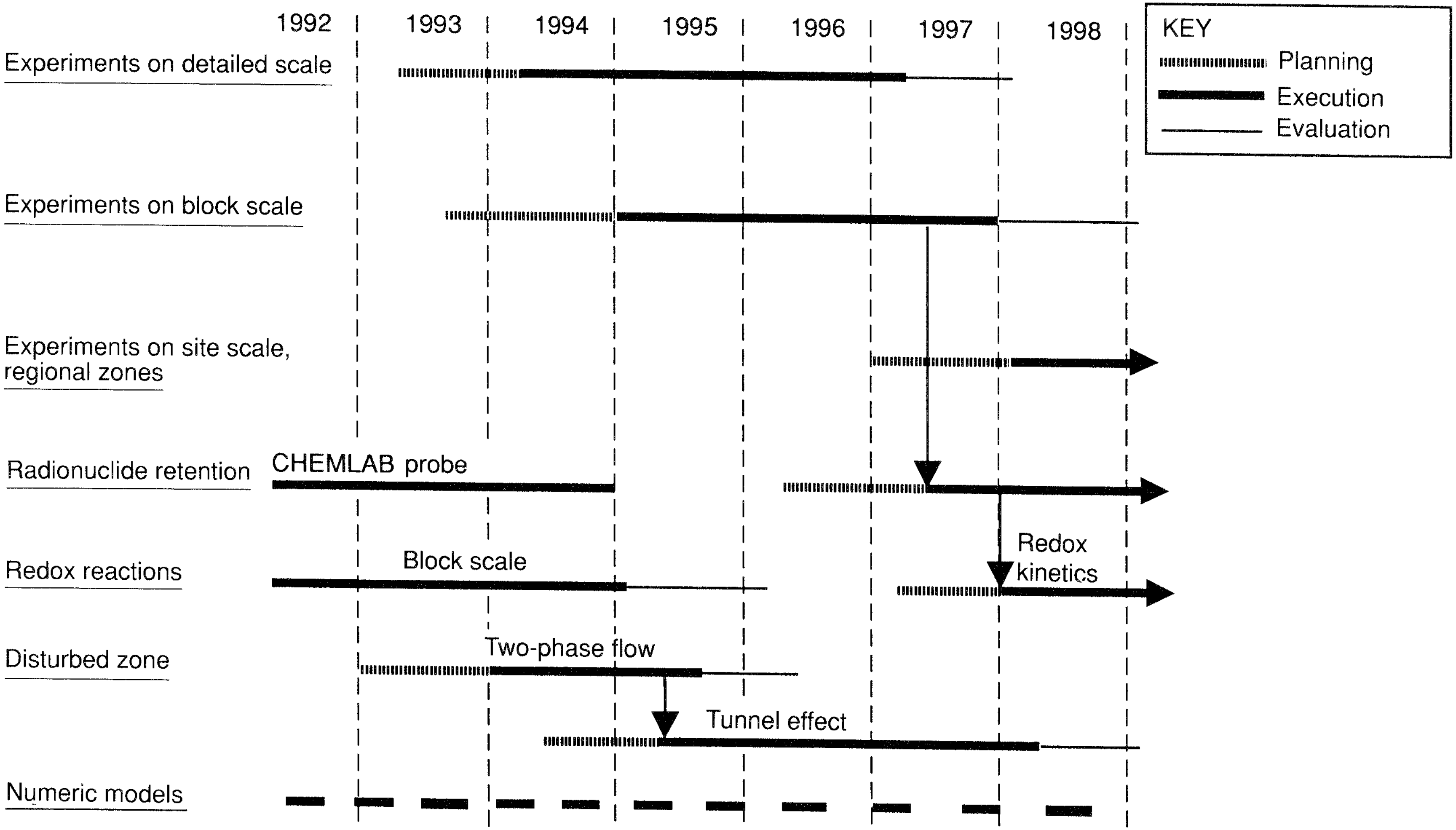

*Figure 7-1. Preliminary timeschedule for operating phase, tests of models for groundwater flow and radionuclide migration.*

**Redox tests** are currently in progress and will proceed according to established guidelines during the next few years. A shift will gradually take place to studying redox kinetics on a detailed scale.

The project **Radionuclide retention** will be carried out on the experimental level at 460 m. Characterization and preparation of suitable test sites will take place within the framework of the project **Tests on block scale**. This project will be commenced in 1995, when it is believed the experimental level will be available. It is estimated that the field tests for the project **Radionuclide retention** can be commenced three years later.

The project **Disturbed zone** will be initiated already during the operating /construction?/ phase with fundamental studies of **Degassing of groundwater and two-phase flow**. The larger-scope **Tunnel effect experiment** will be conducted on the experimental level once it has become available.

An overall schedule is shown in Figure 7-1 for activities for **Tests of models for groundwater flow and radionuclide migration.**

A suitable time to begin **Demonstration of construction and handling methods** has been deemed to be around the year 2000. Certain studies concerning grouting of rock will be carried out before then.

**Tests of important components in the repository system** will commence in 1995. Certain small projects will then be started, such as gas migration in the buffer and thermo-mechanical effects, buffer-rock. The important project **Buffer tests** should not be commenced until results are available from the **Disturbed zone** project.