BACKGROUND REPORT TO
R&D-PROGRAMME 89

# Handling and final disposal of nuclear waste

## Hard Rock Laboratory

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# HARD ROCK LABORATORY

## R&D-programme 89

## Background Report

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# 1 INTRODUCTION

## 1.1 BACKGROUND

In an international perspective, Sweden has come a long way in the development of safe and accepted systems for the management and disposal of radioactive waste.

A complete system for sea transport of spent nuclear fuel from the twelve Swedish nuclear reactors has been in operation since 1982. The spent nuclear fuel will be stored in CLAB for a period of about 40 years up until final disposal. The facility has been in operation since 1985. A final repository for low- and intermediate-level short-lived waste, SFR, has been in operation since April 1988.

The Swedish waste system is almost complete. The facilities that still remain to be built and sited are a final repository for the long-lived waste, consisting mainly of the spent nuclear fuel, and an encapsulation plant for the spent fuel.

The purpose of final disposal is to protect human beings and life on earth from all direct effects of the waste. If damages should nevertheless occur to any canister in the protective environment of the repository, any traces of the waste that might then be carried to the surface with the groundwater shall be negligible in relation to the water's natural content of radionuclides. Finally, the repository shall be able to be sealed permanently and thereafter not require any further supervision by future generations.

It has already been demonstrated in the KBS-3 Report in 1983 that it is possible to build and site a final repository in Sweden that meets very high demands on long-term safety.

The final repository described in the KBS-3 Report is based on the principle of:

- isolation of the waste deep down in the bedrock,
- multiple long-lived barriers.

The barriers are divided into engineered barriers – waste form, canister, buffer material – and the natural barrier – the rock.

The engineered barriers prevent or limit contact between groundwater and waste, and retard and impede the dissolution of the waste if such contact should occur.

The primary function of the natural barrier is to provide stable conditions as regards flow and the chemical properties of the groundwater. Furthermore, the rock has a very great potential for retaining most radioactive materials present in the waste. A second function of the natural – or geological – barrier is therefore to prevent or retard the transport of radioactive materials with the groundwater. Other disposal concepts (than the one described in KBS-3) make use of the same principle to achieve safe disposal.

A safety assessment is performed to make sure that the waste will remain isolated in different conceivable, more or less probable situations or scenarios that might occur in the future. Safety assessments have been carried out in Sweden for the final repository for low- and intermediate-level waste – SFR – as well as for various described systems for final disposal of high-level waste or spent nuclear fuel – KBS-1, KBS-2, KBS-3 and WP-Cave. All of these assessments have been carried out with conservative assumptions and different given conditions, particularly with regard to the properties of the geological barrier. The safety assessments for KBS-3 and WP-Cave, for example, therefore contain a number of very conservative assumptions.

An important function of the R&D activities is to broaden the knowledge base so that more realistic safety assessments can be carried out and so that more precise information can be gained regarding the safety margins entailed by different repository concepts. The knowledge base shall be broad enough to permit alternate theories to be tested. It can be mentioned in particular that there are several alternative theoretical models today for describing groundwater flow. A well-characterized rock volume provides an opportunity for testing areas of application and limitations for the different models that are applied.

## 1.2 SITING OF FINAL REPOSITORY FOR SPENT FUEL

Since the end of the 1970s, SKB has carried out extensive studies of the geological conditions at many different sites in Sweden. Investigations have been carried out from the surface and in boreholes down to a depth of 1 000 metres on eight so-called study sites. Furthermore, a great deal of work has been done at the Stripa Mine within the framework of the international Stripa Project. Special research projects focussing on the properties of fracture zones have been carried out at the Finnsjön study site, at the Saltsjö Tunnel, on a tunnel construction site at the hydropower station in Hylte and within the Lansjärv Project. For an account of the results of these studies, the reader is referred to R&D-programme 89 and to SKB's Technical Reports. In summary, these studies show that good geological conditions exist for siting a final repository at many locations in Sweden. The siting question does therefore not have to rest primarily or solely on geological conditions, even though these are important. One conclusion of this is that there is no reason to continue performing only borehole or surface investigations on additional sites. For while such investigations do broaden the database, they do not necessarily lead to increased understanding.

R&D-programme 89 describes the planning for the siting of such a final repository in Sweden. In summary, the plan entails:

| | |
|---|---|
| 1992-94 | Presentation of three candidate sites and execution of pre-investigations. |
| 1994-96 | Approval of two sites for detailed investigations at depth. |
| 1996 | Selection of shaft location and shaft design on both sites. Shaft sinking and rock characterization. |
| 1996-99 | Selection of suitable depth, positioning and layout of a repository on the two sites. |
| 1999 | Selection of first-priority repository site, compilation of preliminary safety report. |
| 2003-06 | Siting decision. |
| 2010 | Start of construction. |
| 2010-15 | Selection of tunnel routing and deposition sequence. |
| 2020-50 | Expansion of repository and successive selections of deposition positions. |

The siting process imposes different demands on background material in different phases. In an early phase, the ability to demonstrate that the site can offer rock volumes with low groundwater flux, favourable chemistry and mechanical stability is of primary importance. As the decision-making process progresses and as the forecast models and safety assessments become more detailed, specific needs will arise for more detailed information.

The evaluation of which knowledge is of importance for a final repository and its siting takes place within SKB's general research. The knowledge is summarized in safety assessments as a basis for different decisions. The assessments also serve as a point of departure for studying the consequences of altered assumptions, models and data and thereby provide a basis for the prioritizing of R&D activities and design modifications. During 1991, SKB will present the results of a new safety assessment for a KBS-3-like repository based on data from, among other places, the Finnsjön study site.

## 1.3 MOTIVES FOR CONSTRUCTION OF THE HARD ROCK LABORATORY

A balanced appraisal of the facts, requirements and evaluations made in connection with the preparation of R&D-programme 86 led to the proposal to construct an underground research laboratory called the Hard Rock Laboratory. This proposal was presented in the aforementioned research programme and was received very positively by the reviewing bodies.

The most important reasons for the Hard Rock Laboratory are:

- verification of surface and borehole investigations,
- testing of methods for detailed site investigations with shaft sinking or tunnelling,
- opportunity, in a realistic environment and on a large scale, to investigate conditions of importance for safety, for example groundwater flow and coupled transport of solutes,
- opportunity, in a realistic environment, to carry and demonstration tests and long-term tests of the interaction between engineered barriers and rock,
- method development for rock engineering works, waste handling and backfilling.

These motives are examined in greater detail in the following.

Investigations of conceivable final repository sites carried out thus far have only involved measurements on the ground surface and in boreholes. Investigations have also been carried out in and from tunnels at Stripa and in connection with certain construction work 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 repository. The construction of the Hard Rock Laboratory provides excellent opportunities for such verification. This verification will permit greater confidence in our ability to judge the suitability of future candidate sites for a final repository even before detailed investigations of these sites have been made. This can facilitate the decision-making process that will lead to technical-scientific acceptance for the proposed candidates.

The detailed investigations of candidate sites that are planned to be carried out during the latter half of the 1990s will include studies of the rock from shafts and tunnels at repository level. These detailed site investigations include the field studies and analyses that are supposed to provide the final confirmation that a selected site is suitable for the final disposal of longlived and high-level radioactive waste. These studies are also supposed to provide sufficient data for adapting the repository to the selected site and for an assessment of the long-term safety of the adapted repository. This assessment shall be included in a siting application and shall show that the site fulfils the requirements in the Act on Nuclear Activities. Some of the technology and methods for carrying out such investigations have been developed and tested at Stripa. However, since Stripa is an abandoned mine, it is not possible to test all aspects of the methods there. Tests in a previously undisturbed area provide additional opportunities for developing and refining the methods before they can be used "for real". On the candidate sites, it is not appropriate to carry out the equivalent of what is known in ordinary industrial development work as "destructive" testing. It is therefore important to have access to the Hard Rock Laboratory where such tests can be carried out.

The central, and at the same time the most complex problem in the assessment of the final repository's long-term safety is the flow of groundwater in the rock's fracture system and the associated transport of substances dissolved in the groundwater. Extensive efforts have been made and are being made to shed light on this problem. Important but by no means exhaustive examples are:

- Extensive measurements of the hydraulic permeability of the rock have been carried out in deep boreholes on all study sites.
- Tracer experiments with non-sorbing tracers have been carried out at Studsvik, Finnsjön, Stripa and Hylte.
- Mappings of water-bearing fracture zones have been carried out via radar measurements and other geophysical surveys at Stripa and at several study sites.
- Tracer tests with sorbing tracer have been carried out in laboratories, as well as in field tests at Studsvik, Stripa and Finnsjön.
- Natural analogs are being studied at Poços de Caldas, Cigar Lake and other projects to provide a picture of the behaviour of natural radioactive and chemically closely-related substances on a geological time scale.
- In parallel with these experimental investigations, great efforts are being made to develop descriptive models and mathematical models for systematizing and interpreting the data and results obtained from the field and laboratory tests.

The future research should above all be devoted to tying together and completing the picture that has been obtained from the previous investigations at different sites. An initial such tying-together attempt is being made within phase 3 of the Stripa Project, where a site characterization and validation test (SCV) is being carried out with respect to a 125 x 125 x 50 m rock volume in a previously uninvestigated portion of the Stripa granite. Prior to the siting of the final repository, a similar tying-together attempt will be carried out on a larger scale to obtain more experimental data for the long-term safety analysis. Such a large-scale test can be carried out at the Hard Rock Laboratory.

When a fundamental design for the final repository has been chosen in the mid-1990s, the different parts included in this system will have to be tested on a realistic scale. Of particular importance is testing and demonstrating the interaction between engineered barriers and rock in as realistic an environment as possible. This will primarily involve long-range tests and demonstration trials on a full-size or representative scale. "Destructive" testing may also be required. This is yet another motive for building the Hard Rock Laboratory.

Prior to the construction of the final repository, it is necessary to develop and verify the methods and the technology needed for constructing tunnels and storage galleries, for determining exactly where the waste is to be emplaced, for handling the waste underground, for depositing the waste at the intended position and for backfilling and sealing the different parts of the repository. All of these activities must be carried out with documented quality in order to satisfy the safety requirements. Many of these techniques can be developed and tested in the Hard Rock Laboratory. Access to such a laboratory will provide good opportunities for satisfying the quality requirements.

## 1.4 SITING OF THE HARD ROCK LABORATORY

In R&D-programme 86, it was stated that a new underground laboratory should preferably be located in a place where existing services and the kind of infrastructure needed for research work already existed. One of the nuclear power sites should be considered first, such as Simpevarp in the municipality of Oskarshamn.

Investigations in the Simpevarp area, see Figure 1-1, were begun in the autumn of 1986 and have since continued on a relatively large scale in 1987, 1988 and the spring of 1989. On the basis of the results obtained, SKB has made a decision in principle, to locate the Hard Rock Laboratory on the southern part of the island of Äspö – see the map in Figure 1-1. 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, for example, stationing of researchers, meetings etc. The fact that OKG owns the land in question facilitates the leasing of the necessary land.

This siting presumes the approval of the concerned authorities, which is expected during 1990. In August 1989 the government decided that the Hard Rock

Laboratory should be reviewed under the Act on the Conservation of Natural Resources. In connection herewith SKB has decided to make certain changes in the layout of the laboratory which will reduce the environmental impact.

The exact site of the Hard Rock Laboratory, Äspö, will not be considered as a site for the final repository. However, if appropriate geological conditions are found to exist in the vicinity, this could be one of the candidate sites that is subjected to detailed investigation prior to the final siting of the final repository.

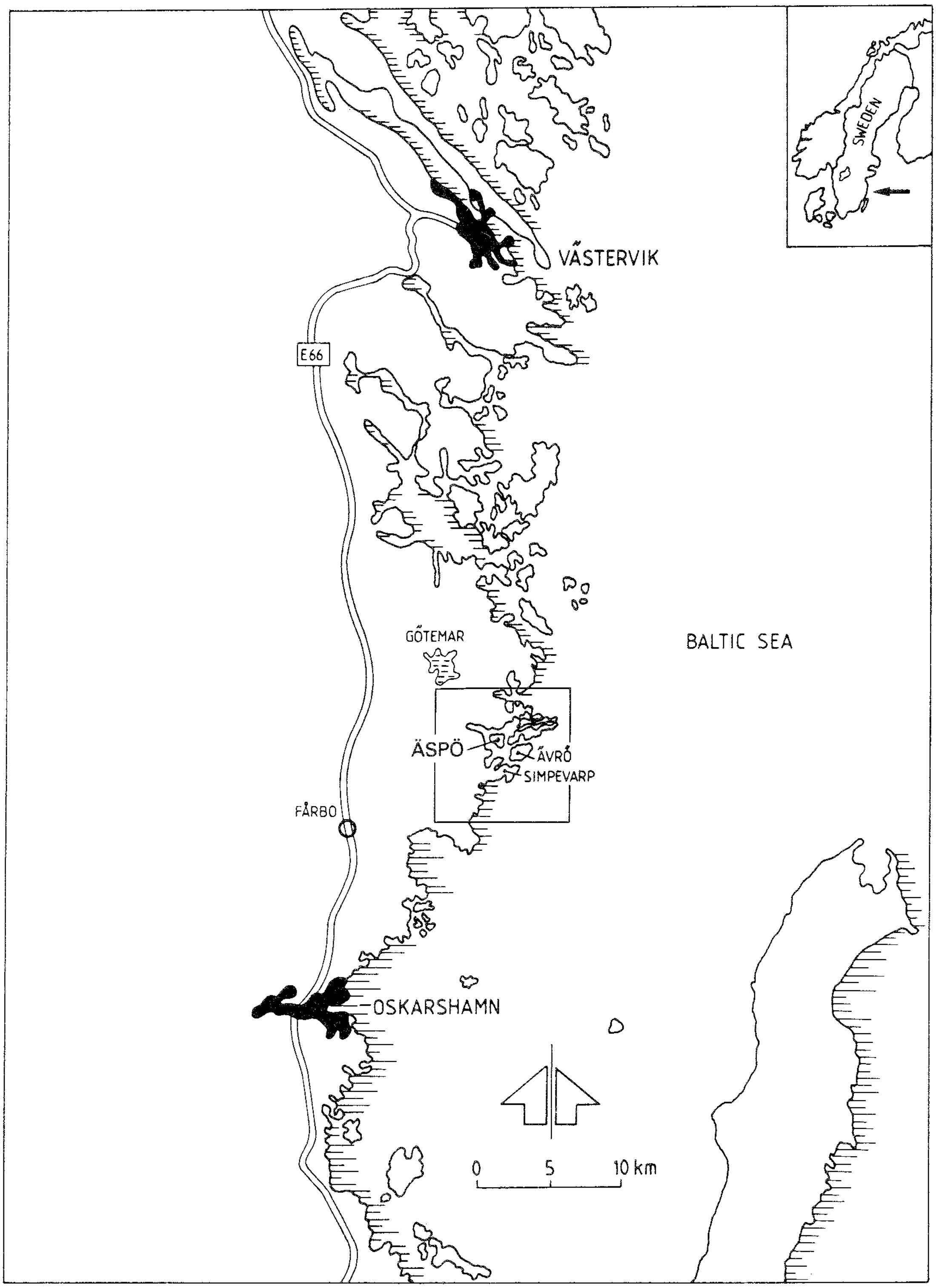


*Figure 1-1. The Simpevarp area with environs.*

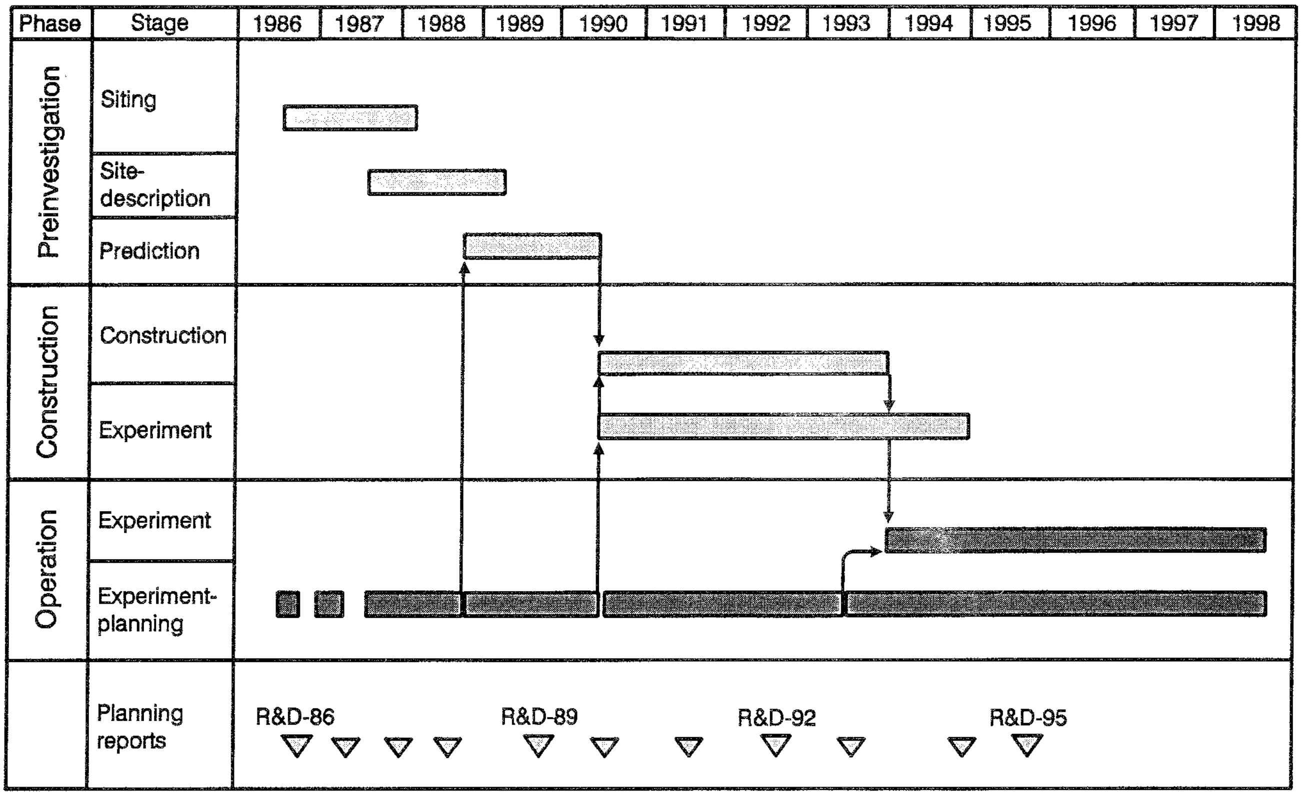


*Figure 1-2. Time schedule.*

## 1.5 EXECUTION OF THE RESEARCH WORK

Like SKB's other R&D work, the R&D activities at the Hard Rock Laboratory will mainly be contracted out to universities, institutes of technology, research institutions, consultants, industrial companies and other Swedish and foreign researchers. This will enable a high level of competence and quality to be maintained. The most suitably qualified experts can thereby be chosen for different investigations and experiments. Different alternative methods or models can be tested for certain questions.

The research programme for the Hard Rock Laboratory will be continuously revised and deepened. The present programme is the fourth revised version. It is, however, the first that has been coordinated with R&D-programme 89. The proposals for investigations and tests during the operating phase have been arrived at in consultation with leading experts and compiled by SKB. In the future, the programme will be revised in connection with the three-year R&D programmes. In the interim, detailed plans will be made for the different investigations and tests to be carried out. A general time schedule for the project is shown in Figure 1-2.

The project is headed by a project group responsible for execution of the work. The thrust and contents of the research programme will be determined by a programme group within SKB's research department. A reference group has been appointed to provide advice and viewpoints on the programme and its results. Figure 1-3 shows the current organization.

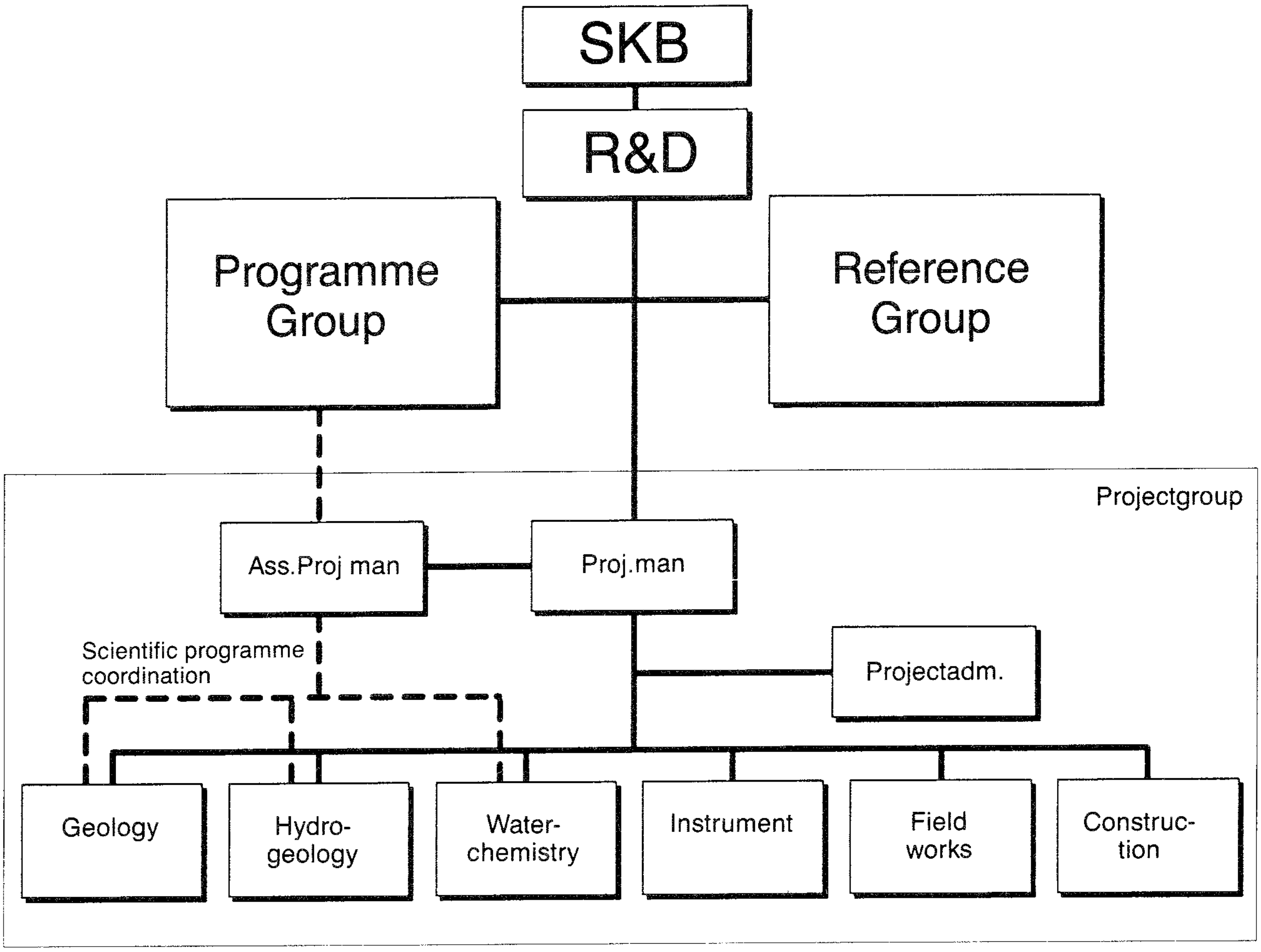


*Figure 1-3. Organization of the project.*

# 2 GOALS

Against the background of the motives presented in section 1.3 and the time schedule presented in section 1.2, SKB has decided to construct an underground research laboratory. The purpose of the Hard Rock Laboratory is to provide an opportunity for research and development in a realistic and undisturbed underground rock environment down to the depth planned for the future final repository.

The Hard Rock Laboratory shall constitute an important complement to the other work being conducted within SKB's research programme.

Demands on the quality of the research are very high and the overall ambition is that the laboratory should become an internationally leading centre of research and development regarding the construction of final repositories for highlevel waste.

## 2.1 MAIN GOALS

The R&D work in the underground laboratory has the following main goals:

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

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

## 2.2 STAGE GOALS

To meet the overall time schedule for SKB's research work, the following stage goals have been set up for the activities at the Hard Rock Laboratory.

Prior to the siting of the final repository for spent fuel in the mid-1990s, the activities at the 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 investigation methodology**
   - refine and verify the methods and the technology needed for characterization of the rock in the detailed site investigations.

As a basis for a good optimization of the final repository system and for a safety assessment as a basis for the siting application, which is planned to be submitted a couple of years after 2000, it is necessary to:

3 **Test models for groundwater flow and transport of solutes**
   - refine and test on a large scale at repository depth methods and models for describing groundwater flow and transport of solutes in rock.

In preparation for the construction of the final repository, which is planned to begin in 2010, 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 can be refined and tested so that high quality can be guaranteed in the construction, design and operation of the final repository, and

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

These tests shall be able to be carried out on a sufficient scope as regards time and scale to provide the necessary support material for Government approval of the start of construction. Certain tests may therefore have to be started in the mid-90s.

## 2.3 COMMENTS ON THE GOALS

The main goals for the Hard Rock Laboratory are to refine and/or test three different kinds of abilities prior to the construction of a final repository.

- Technology for characterizing rock.
- Methodology for adapting a repository to the character of the rock.
- Methodology for evaluating the safety performance of the rock.

The properties of the rock that are of importance in different phases will vary. The testing of the quality of methods for rock characterization that is to be done in the Hard Rock Laboratory will be coupled at an early stage to the ability to determine the groundwater flow and chemistry at repository depth on the basis of pre-investigations. As the decision-making process progresses and as the forecast models and safety assessments become more detailed, specific requirements will be made on the detailed information.

## PRE-INVESTIGATION METHODS

### (Stage goal 1)

Before detailed investigations begin on the candidate sites, the sites must be approved by different authorities. The support material for this approval will be the results of the pre-investigations planned for the years 1992-94.

The programme for the pre-investigations will be based, among other things, on experience from study-site investigations from the Stripa Project and from the Hard Rock Laboratory. It is important to clarify the precision of the pre-investigations prior to taking a decision on the detailed investigations. This can be done in connection with the construction of the Hard Rock Laboratory.

Investigation of the rock is an iterative process that can be carried out in a number of stages. Findings can be submitted after geological map studies. Preliminary models of the bedrock can be devised and then supplemented in subsequent investigation stages. In the Hard Rock Laboratory, such descriptions will be prepared in stages to different scales. Regional scale will be used for orienting the site in a tectonic context and for describing the most important zones of groundwater flow and possible rock movement. The construction scale, about 1 km$^2$, is relevant for siting the repository in relation to existing fracture zones and for identifying suitable rock volumes for the location of shafts etc. A description on the 100-metre scale is relevant for identifying which volumes are suitable for waste disposal. Rock descriptions on the 10-metre scale will be used to describe the near field around the waste. The metre scale and smaller is important for studies of chemical interaction between rock and 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 investigations carried out in special investigation tunnels and shafts can considerably deepen this 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 assessments made on the basis of pre-investigations lead to the same principal conclusions that are later obtained after detailed investigations have been carried out.

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

## DETAILED SITE INVESTIGATIONS

### (Stage goal 2)

The detailed investigations will necessarily entail alteration of the natural groundwater situation. It is thus important to be convinced that the essential data have been collected before tunnelling or shaft sinking has begun. The detailed investigations must be thorough and completely documented. The pre-investigation and construction phases in the Hard Rock Laboratory provide excellent opportunities to develop and test procedures for the detailed investigations under realistic conditions. The Hard Rock Laboratory will demonstrate the deepening of knowledge that is possible to achieve in relation to the assessments made during the preliminary investigation phase.

## MODELS FOR GROUNDWATER FLOW AND TRANSPORT OF DISSOLVED SUBSTANCES

### (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 groundwater flow on the site. This understanding is required for positioning of the waste, for determining the thickness of the engineered barriers, for analysis of different release scenarios and the eventual sealing of the repository in the best manner. The Hard Rock Laboratory provides an opportunity for practically applying different theoretical models for how groundwater and substances dissolved therein are transported to the isolated waste and how the outward transport of radioactive materials could take place.

## QUALITY OF CONSTRUCTION AND EXECUTION
### (Stage goal 4)

The final repository consists of a large number of identical parts. A KBS-3 repository, for example, consists of several thousand canisters, each surrounded by highly compacted bentonite and placed in a deposition hole. The different components (fuel, canister, bentonite, rock) interact to ensure safe disposal. Other important components are eg sealing plugs for shafts, boreholes or tunnels, grouting shields for diverting mobile groundwater, and tunnel backfill. All of these parts must be executed with a certain minimum quality in order for the repository as a whole to meet the safety requirements. Prior to the application for a building permit, it is urgent to demonstrate that it is possible to maintain this minimum quality. A progressive increase in the degree of detail of the description will take place during the preliminary and detailed investigations. This description and understanding will deepen as the repository is constructed. It is important to demonstrate how data will be collected and analyzed during the repository's construction phase. Before construction begins, different methods for excavating tunnels and deposition holes, for example drilling/blasting or full-face boring, can also be demonstrated. The measurements and analyses to be performed before selection of the rock volumes where the waste is to be emplaced will be demonstrated. Methods for quality control and quality assurance in the execution of different parts of the final repository system can also be developed and tested, for example in connection with fullscale tests.

## FULL-SCALE TESTS
### (Stage goal 5)

In a well-characterized rock mass, full-scale tests can be carried out on selected parts of the disposal concept. These tests may have to be begun in the mid-90s and proceed for a long period of time. Tests can be carried out on individual components in the repository system. Interactions between rock and buffer can be analyzed. The influence of, for example, temperature variations can be evaluated. Before permission is given for closure of the facility, the methods for sealing the facility can be demonstrated. The results of these tests will serve as support material for licencing applications at different stages. They are also expected to contribute towards greater confidence in and acceptance of the chosen concept.

# 3 RESEARCH PROGRAMME - OVERVIEW

## 3.1 GENERAL

This chapter provides an overview of the activities that have been carried out and that are planned in order to meet the goals formulated in the preceding chapter. For a more detailed account, see the appendices to the report.

As with SKB's other research programmes, it is vital that the details of this programme be formulated as data and models become available. The present programme is the fourth revised version of the research programme.

The work with the hard rock laboratory is divided into three phases – pre-investigation, construction and operating phase – as evident from the time schedule, Figure 3-1.

In the **pre-investigation phase**, a site will be chosen for the laboratory. The ambient conditions in the bedrock will be described. In parallel with the pre-investigations, the project's construction and operating phases will be planned.

During the **construction phase** 1990-1994, a number of investigations and tests will be conducted in parallel with the construction activity. The tunnel will be excavated down to the 500 m level in stages. A preliminary layout of the laboratory is shown in Figure 3-2.

The **operating phase** will commence in 1994. The thrust of the investigations and tests to be carried out during the operating phase is described in this programme. The final programme for the operating phase will be adjusted on the basis of the results of other projects and experience gained in the construction phase.

Table 3-1 briefly presents the topics that will be explored in the Hard Rock Laboratory and how the weight given to the activities is to be distributed over time.

The research can be divided into three main areas:

- site investigations,
- methods for repository construction,
- pilot tests with repository systems.

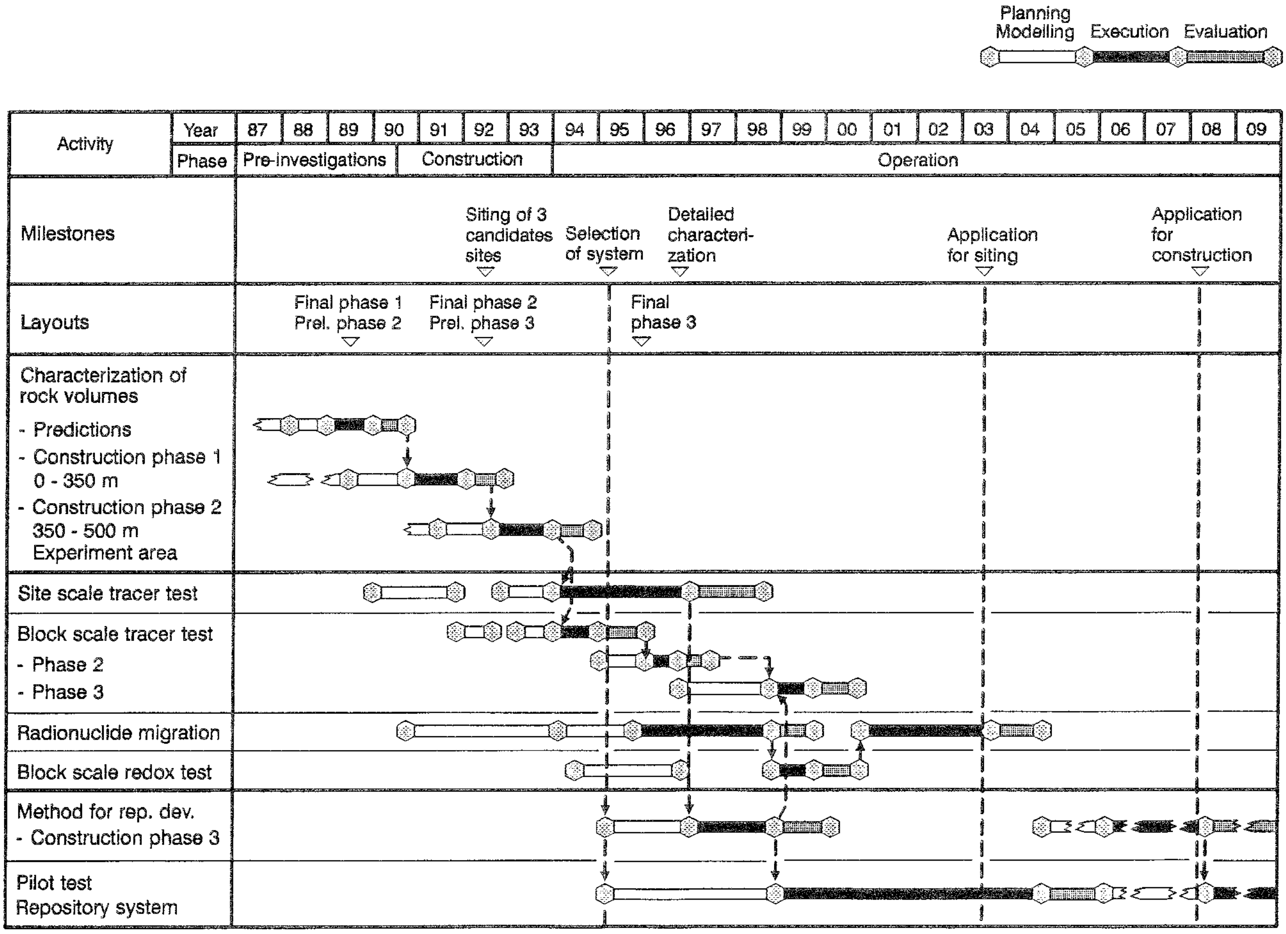


*Figure 3-1. General time schedule for investigations and tests.*

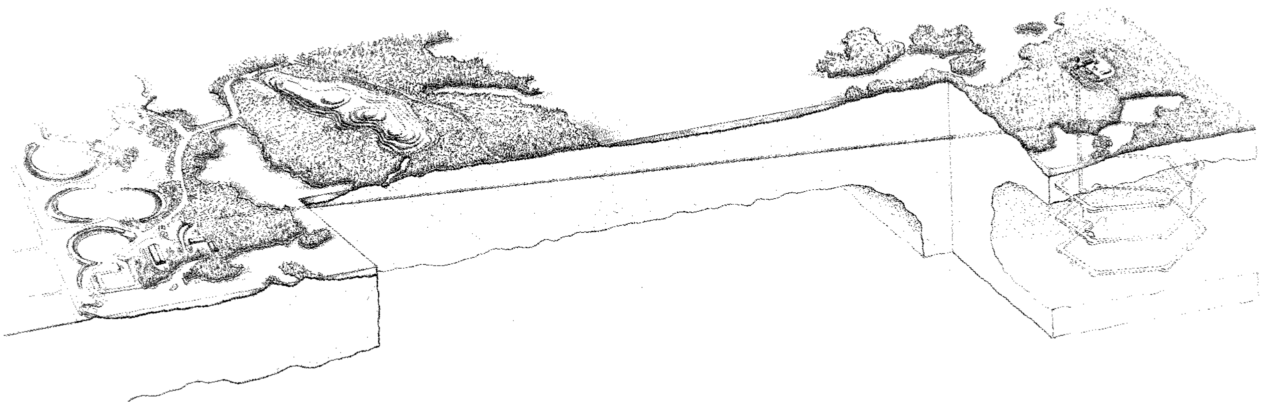


*Figure 3-2. Schematic design of the Hard Rock Laboratory.*

It is foreseen that the final disposal of spent nuclear fuel will take place with very long-lived canisters. This means that all activity will be contained over a very long time span.

**Site investigations** will involve executing and testing the investigations, analyses and calculations of the conditions on a given site that are needed to design a safe final repository. Of importance is to demonstrate the ability to locate rock of different qualities. This is needed in order to be able to designate suitable storage volumes where access to the repository level can take place and where continued detailed investigations are to be carried out.

It is also possible to demonstrate how storage tunnels and waste can be positioned in a repository area so that zones of movement are avoided and so that low groundwater flux is obtained, especially in the near field. The flow paths in the rock need to be located and the groundwater flux in the near field needs to be described. The chemical composition of the groundwater is of great importance for judging the suitability of the site. For calculating the transport of radionuclides, it is necessary to define discharge areas, the groundwater flux and the geometry of the flow paths. Mechanical stability is required during repository construction.

**Methods for repository construction** shall be tested and developed to show how the construction process can be utilized to characterize the near field on the site finally selected for the final repository. Furthermore, technology for full-face boring/blasting of storage tunnels, for making canister holes, for injection grouting etc will be developed and tested.

**Pilot tests with repository systems** will be carried out to demonstrate and, wherever possible, verify the design of important parts of the repository system that are finally chosen for the long-lived waste. Pilot tests will be conducted in rock that has been characterized with the methods tested in the earlier phases of the project.

## 3.2 PROGRAMME FOR THE PRE-INVESTIGATION PHASE

Investigations of the bedrock will be undertaken both from the ground surface and in boreholes. Data will be compiled in conceptual models as a basis for siting of the laboratory, design of the facility and numerical calculations of groundwater flow on different scales.

The preliminary investigation phase is divided into the following stages:

- siting,
- site description and
- prediction,

of which the first two have been completed and the results reported.

The investigations were begun in the autumn of 1986 and studies have been carried out on several different scales, both regional and local. The work was focussed almost from the start on a siting near the Simpevarp area, which has a good infrastructure for the planned activities.

The completed investigations have shown that favourable conditions exist on the island of Äspö north of Simpevarp for constructing the Hard Rock Laboratory, of which the following can be mentioned:

- A relatively homogeneous rock block with few well-defined groundwater-conducting structures exists on southern Äspö, where the access tunnel to the laboratory can be built.

Table 3-1. **Overview of research topics for the Hard Rock Laboratory.**

| RESEARCH TOPIC | PRE-INVES-TIGATION | CONSTRUCTION PHASE | | OPERATING PHASE |
|---|---|---|---|---|
| | | STAGE 1 | STAGE 2 | |
| • **SITE INVESTIGATIONS WITH CALCULATIONS** | | | | |
| **Demonstratabilty to locate rock of different qualities** | | | | |
| – on regional scale, > > 1 000 m | B | C | C | C |
| – on facility scale, 100 – 1 000 m | B | A | A | A |
| – on block scale, 10 – 100 m | C | C | A | A |
| **Describe flowpaths for groundwater** | | | | |
| – on regional scale | C | C | C | C |
| – on facility scale | B | A | A | A |
| – on block scale | C | B | B | A |
| **Describe groundwater flux** | | | | |
| – on regional scale | A | B | C | C |
| – on facility scale | A | A | B | B |
| – on block scale | B | B | A | A |
| **Describe chemical composition of groundwater** | | | | |
| – on regional scale | C | C | C | C |
| – on facility scale | A | B | B | B |
| – on block scale | C | B | B | A |
| **Transport of solutes** | | | | |
| – on regional scale | C | C | C | C |
| – on facility scale | B | B | B | A |
| – on block scale | C | C | B | A |
| **Mechanical stability of rock** | | | | |
| – on regional scale | B | C | C | C |
| – on facility scale | B | C | C | B |
| – on block scale | C | C | C | B |
| • **METHODOLOGY FOR REPOSITORY CONSTRUCTION** | | | | |
| Investigation methodology | C | C | B | A |
| Full-face boring/blasting | C | C | C | B |
| Hole-making technology | C | C | C | B |
| Injection grouting technology | C | C | C | B |
| • **PILOT TESTS – REPOSITORY SYSTEMS** | | | | |
| Effective temperature on bentonite and rock | C | C | C | B |
| Effect of "Disturbed zones" on groundwater flux | C | B | B | B |

**LEGEND:** A High priority
B Medium priority
C Low priority

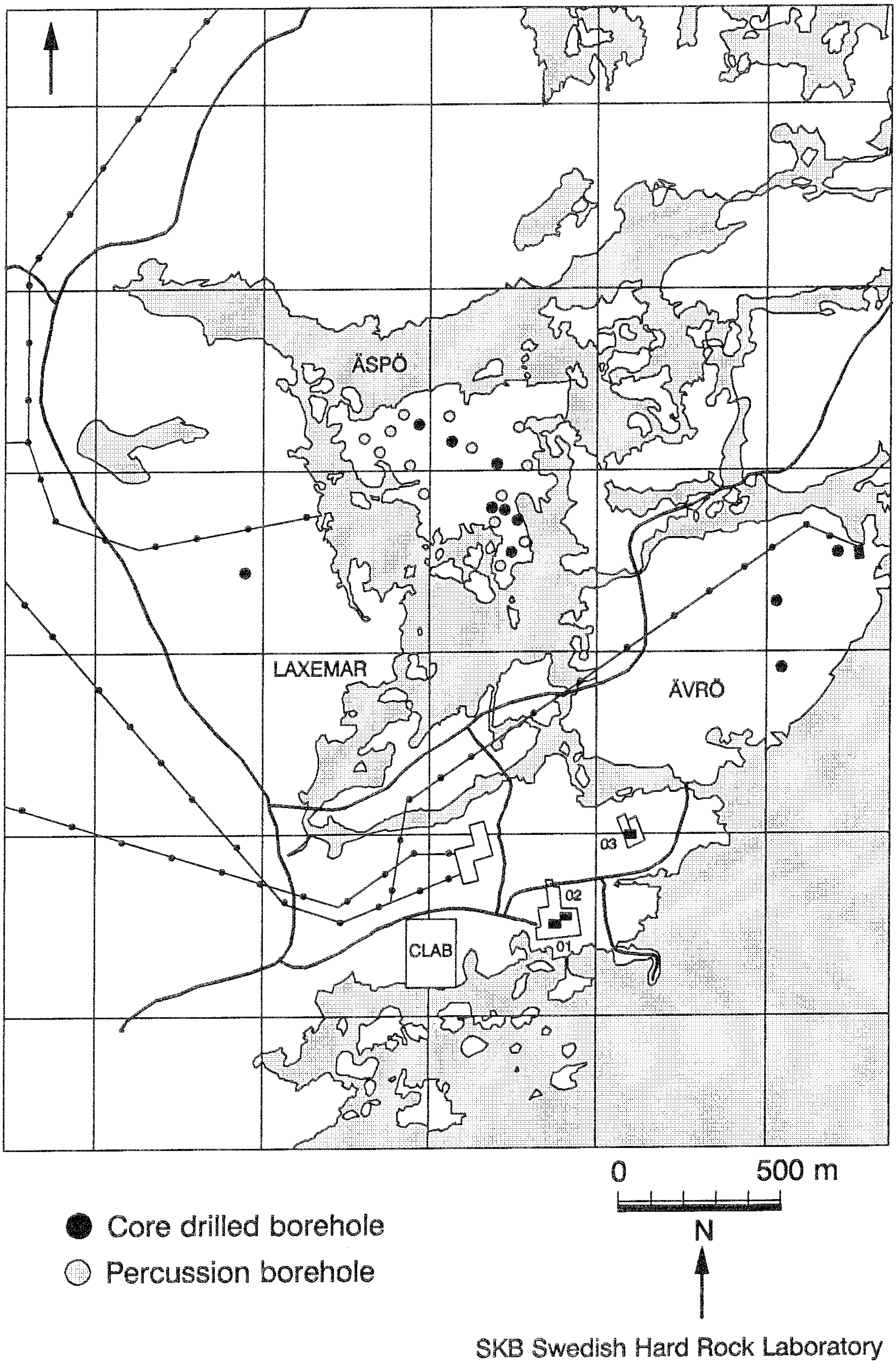


*Figure 3-3. Äspö with environs.*

- Nearby the above, are a central shear zone and areas with very homogeneous Småland granite.
- Areas below the surface of the sea are available immediately adjacent to Äspö.

The results from the **siting stage** have been reported in SKB Technical Report 88-16. The regional-scale rock description shows that the Simpevarp area consists primarily of granitic bedrock (Småland granite) with intrusions of basic rock types, greenstones. The information from the geological and geophysical surveys shows a tectonic picture of the Simpevarp area dominated by a nearly orthogonal system of first-order fracture zones in the N-S and E-W directions. Aside from this system, there are second-order zones running in the NW and NE directions that also form a nearly orthogonal system. There are probably also flat, subhorizontal zones.

Of importance for numerical models of 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. The siting stage also included percussion drilling programmes on three sites to gather data for a chemical characterization of the superficial groundwater. It was judged that both Äspö and Laxemar were suitable sites for a hard rock laboratory, see Figure 3-3.

The **site description stage** has been described in SKB Technical Report 89-16. The continued investigations for siting were focussed primarily on Äspö. Laxemar will be used as a reference area where, for example, natural variations in groundwater levels can be followed and compared with the disturbed conditions that will exist on Äspö after the laboratory has been built. Four holes have been cored, the deepest down to a depth of 1 km. In addition to high quality core mapping, extensive geophysical measurements have been carried out, along with hydro tests on several scales and hydrochemical analyses of the sampled groundwater from different levels. Thorough surface investigations have been carried out on Äspö, including seismic profiles, outcrop mapping, geophysical measurements and cross-hole interference tests. In the cored holes drilled on southern Äspö, Småland granite is the dominant rock type down to a depth of more than 300 m, where it is supplanted by a quartz-poorer variety of the Småland granite called diorite. Zones of different character exist on Äspö.

Southern Äspö has been proposed as a site for the Hard Rock Laboratory. Äspö offers conditions for scientific experiments of great interest for a safe final repository. Äspö also offers the conditions necessary for satisfactory execution of the qualified construction project. With a view towards future tests and experiments, it would be an advantage if different types of rock and zones could be studied in the laboratory. This variation is available on Äspö with environs.

Hydrochemical conditions on Äspö are also representative of the conditions that would prevail in the event of a coastal siting of an underground facility. The groundwater is fresh near the surface and saline at greater depth. Several types of numerical calculations of groundwater flow have also been carried out in the site description stage, see further Chapter B4.

The site description presented in SKB TR 89-16 has since been supplemented in the **prediction stage** with the drilling of an additional four cored holes. These results and the associated numerical calculations will be described in a Technical Report in the spring of 1990. Predictions will be made to different scales, termed the regional scale, > >1000 m, the facility scale, 100–1000 m, the block scale, 10–100 m and the detail scale, 0–10 m. The predictions to be made, the expected outcome, the grounds for validation and the measuring accuracy striven for will also be defined for each scale. The predictions for each scale will be grouped according to research fields and will involve testing of conceptual models, groundwater flux, chemical environment, transport of solutes in groundwater and mechanical stability of the rock. Calculations will be carried out on different scales and compared before the start of the construction phase with pressure and flow measurements in boreholes and with hydrochemical data, especially the salinity of the water. The geological, hydrological and hydrochemical predictions made during the prediction stage will be evaluated during the construction phase.

In order to check the conceptual model prepared in the site description stage, a long-range pumping test will be carried out during the summer of 1989. The measurement results will be used to evaluate the predictive calculations carried out before the long-term pumping. The results will also be used to prepare the final calculation model of the groundwater changes that will take place when the laboratory is built. A qualified radial tracer test will also be carried out before the construction phase begins. An evaluation of the longterm pumping and tracer tests will be presented in a Technical Report in 1990.

In August 1989 the government decided that the Hard Rock Laboratory should be reviewed under the Act on the Conservation of Natural Resources. In connection herewith SKB has decided to make certain changes in the layout of the laboratory which will reduce the environmental impact. The new layout of the laboratory will influence the detailed planning for how the pre-investigation stage is concluded.

## 3.3 PROGRAMME FOR THE CONSTRUCTION PHASE

### 3.3.1 Planning

During the construction phase, investigations will be carried out to validate expectation models reported during the pre-investigation phase. Furthermore, data will be collected for progressive improvement of previous predictions. The investigations will be carried out both along the surfaces of the access tunnel and in boreholes drilled from the ground surface and from the tunnel. Since favourable properties of the bedrock nearest the deposition holes and deposition tunnels are of the greatest importance for the safety of a final repository, it is essential that the degree of detail in the investigations during the construction phase be gradually increased.

Investigations performed on the future main level, about 500 m below the surface, will be more detailed than the investigations performed at the start of tunnelling. The investigations carried out during construction of the access tunnel will therefore be divided into stages as follows:

Stage 1 – Excavation of the access tunnel to a depth of 350 m, where the tunnel is expected to pass through the granitic rock and enter the dioritic. Here there will be an opportunity to compile and evaluate the data obtained and compare them with expectation models prepared previously.

New investigation results will provide a basis for new expectation models for the deeper-lying parts of the Hard Rock Laboratory. At the same time, an evaluation of the strategy and measuring methods used for the investigations carried out down to a depth of about 350 m will be carried out.

Raise boring to the surface will also be carried out during this stage.

Stage 2 – Excavation driving of the tunnel down to a depth of about 500 m. The investigations along this stretch will be more detailed than the previous ones to permit a better description of the near field around the access tunnel. Experience gained from the investigations carried out down to a depth of 350 m will be used to determine an optimal investigation programme.

At a depth of about 500 m, the results obtained will be compiled, evaluated and compared with previous expectation models.

The construction stage also includes excavation of galleries for some of the tests that will be carried out during the operating phase and continued excavation of the communications shaft down to a depth of about 500 m.

If later investigations within the framework of the general research programme should show that the final repository should be situated deeper than about 500 m, a further extension of the tunnel to greater depth may be considered.

The work during the construction phase will largely be focussed on geological, hydrological and hydrochemical aspects.

The geological, hydrological and hydrochemical investigations and tests are of great importance for the main goals of the Hard Rock Laboratory: "To test the quality and usefulness of methods for rock characterization", "To further develop and demonstrate methods for design, planning and construction" and "To gather material and data for safety assessment". The work during the construction phase is also closely linked to the stage goals of the Hard Rock Laboratory: "Verify preinvestigation methods" and "Establish detailed investigation methodology". In addition, the investigations are of fundamental importance for the planning of tests and experiments to be carried out during the operating phase.

### 3.3.2 Geological Investigations

As far as geology is concerned, there are a number of both geological and geophysical methods available to assist in describing the composition and structure of the rock mass. The relevance of the different methods, both generally and in the local geological environment, are very incompletely documented, however. This is particularly true of conditions at great depth in crystalline bedrock. The overall goals of the geological documentation during the construction phase can therefore be summarized as follows:

- Evaluate to what extent the pre-investigation methodology used has provided an accurate description of the spacial distribution of rock types, large and small fracture zones and the fracture geometry and minerals of the rock mass in different geological environments and at different depths.
- Establish the relevance of different investigation methods as regards rock types, structures, stability and hydraulic conductivity with respect to geological environment and depth.
- Prepare a good forecast for the geological environment that will be encountered during the second construction stage and during the mining of the 500 m level.
- Develop and test methodology for detailed geological investigations on candidate sites for a final repository.

The investigations are of fundamental importance for testing, developing and demonstrating the methods and the technology required for the detailed site investigations.

The geological expectation models will be devised primarily with respect to lithology and structures. Predictions will be made on different block scales for different geological environments. An effort will be made to define different lithological units and to describe the structure of the rock mass with regard to orientation and character.

Geological documentation of tunnels, shafts and boreholes will be done continuously in connection with the construction of the facility. The outcome will be compared with the expectations models prepared on the basis of results from the pre-investigations.

### 3.3.3 Geohydrological Investigations

As far as geohydrology is concerned, only a few qualified tests have been carried out to test the accuracy of models for groundwater flow in large rock volumes. The overall goals of the geohydrological investigations during the construction phase can be summarized as follows:

- evaluate to what extent the pre-investigation methodology used has provided an accurate description of the ambient groundwater situation in different geological environments and for different depths,
- document the geohydrological conditions in the rock volume from tunnels and rock caverns on different scales and make geohydrological operating forecasts for the blasting work,
- iteratively with the documentation, validate the different-scale models of the influence of the Hard Rock Laboratory on the steady-state geohydrological conditions,
- with the new data continuously being gathered during the construction phase, progressively refine and improve the forecasts of geohydrological conditions at deeper levels,
- validate the updated expectation models of geohydrological conditions at deeper levels, including the 500 m level,
- develop methods for detailed geohydrological investigations on candidate sites.

In order to achieve these goals, it is necessary, as during the preliminary investigation phase, that investigations be carried out in the field, that the data obtained be analyzed and processed integrally with the geological and geohydrochemical investigations, and that the results be integrated into qualitative and quantitative models. The investigations are of crucial importance for the description of the rock in both the far field and the near field.

Records will be kept during the construction work of rock types, fracture content, reinforcing work etc. These records will also include data on water seepage in terms of quantity and location.

An action programme describing how the observations are to be carried out in connection with injection grouting and extensive reinforcing work will be drawn up. The programme will also define the limits for when injection grouting is to be carried out. It will also include guidelines for when side tunnels are to be arranged.

To investigate, describe and model conductive zones without disturbing and being disturbed by the construction process, it is planned that side tunnels will be driven out from the access tunnel. A side tunnel will be blasted out if rock requiring extensive sealing and reinforcing work is encountered.

Probe holes will be percussion-drilled from the sides of the tunnel at the face. Pressure buildup tests and, if required, packer seal measurements will be carried out in the holes, which will be drilled diagonally forward. These pilot investigations will be used to provide operating forecasts in combination with data from the tunnel and to supplement the database with geohydrological data collected underground. The boreholes will also be used for water sampling.

In addition to the probe holes that are drilled regularly at the tunnel face, the observation network underground will be supplemented to characterize and measure the pressure in conductive zones. For this purpose, percussion boreholes are planned to be drilled with multi-packer systems along the tunnel run.

### 3.3.4 Geohydrochemical Investigations

Investigations aimed at clarifying geohydrochemical conditions in the bedrock will be carried out during the pre-investigation phase. This work will be carried out in stages that alternate between measurement, evaluation and prediction, where the collected results are used to predict the conditions and the changes expected during the construction phase. Since the groundwater is mobile, a drainage of raises and tunnels will bring about a high rate of groundwater flux. Accordingly, the changes that take place in water composition will reflect the geohydrological conditions. The goal of the hydrochemical investigations during the construction phase is to study changes in water composition and relate them to the predictions made during the preliminary investigation phase. The goals of the hydrochemical investigations during the construction phase therefore include the following elements:

- follow changes in the interface between saline and fresh water,
- study the transport of solutes in a large volume of rock,
- obtain material for validation of groundwater flow and transport models on a realistic scale,
- follow changes in the redox conditions in the groundwater,
- follow changes in the chemical composition of fracture minerals and determine the redox kinetics of the groundwater-fracture-mineral system,
- develop and test methodology for detailed geohydrochemical investigations on candidate sites.

The work includes studies of changes in the chemical composition of the water (natural tracers) as well as conservative non-interacting tracers injected in surrounding boreholes and in boreholes drilled from tunnels as well as through seepage into the facility. The natural tracers should be able to describe the flow paths of the water in the uppermost stratum of the rock, while the injected tracers shall describe the flow paths in the deeper-lying rock.

The fresh water cushion on Äspö will be used to study the flow paths in the near-surface rock (about 100 m). Owing to pressure head drawdowns in the tunnel, fresh water will run down and reach the tunnel in those points where the connection upward is good. In order to study the flow paths in the deep rock, tracers will be injected in conductive zones via the cored holes previously drilled from the surface. Each injection point will have its own tracer and injection can take place continuously throughout the construction phase or in pulses at constant time intervals.

Groundwater sampling will take place:

- in percussion boreholes drilled into the rock from the access tunnel,
- at points where water seeps into the tunnel through the walls and roof,
- in the drainage ditches,
- in fracture zones intersected by the tunnel.

The purpose of the sampling in the boreholes is to clarify changes in the chemical composition of the water. In addition, any drilling water residues from drilling of the deep cored holes and any added tracers will be detected.

## 3.4 PRELIMINARY PROGRAMME FOR THE OPERATING PHASE

After the third stage of the construction phase, the operating phase of the project will begin. The planning is concentrated on the following proposed tests:

- large-scale tracer tests,
- block-scale tracer tests,
- radionuclide migration,
- block-scale redox tests,
- methodology for repository construction,
- pilot tests, repository systems.

**Large-scale tracer tests** are aimed at characterizing transport in the far field. In order to study the site-specific flow paths existing in the bedrock around the Hard Rock Laboratory, tracer tests will be carried out to different scales. As described in Appendix B4, a large-scale tracer test will be started in the steady-state phase before the start of construction and continue throughout the transient construction phase. The results of this test will serve as a basis for planning of large-scale tracer tests during the operating phase. The goal of the large-scale tracer test during the steady-state operating phase is to:

- study the transport of solutes in a large volume of the rock,
- provide a basis for validation of models for groundwater flow and transport on a realistic scale.

The work is of great importance for the main goals of the Hard Rock Laboratory: "To test the quality and usefulness of methods for rock characterization" and "To collect material and data for safety assessment". Furthermore, the test will provide material for the stage goal to "Test models for groundwater flow and solutes", which is needed for a siting application for the final repository. Together with the tracer tests performed during the construction phase, with the block-scale tracer tests, with hydraulic tests and interference tests, and with similar investigations on other sites (Stripa, Finnsjön), the obtained data will provide a broad database on groundwater flows and transport paths on different scales and under different conditions. This database will be used to test, calibrate and, where possible, validate models for groundwater flow and transport of solutes in fractured rock. The models shall above all be used in the assessment of the long-term safety of the final repository that will be submitted together with the siting application. They should also be able to be used for optimization of the final repository. Furthermore, the database will be able to be further supplemented with data from detailed investigations on the proposed final repository site(s).

**Block-scale tracer tests** will be conducted on an intermediate scale, about 10–100 m.

The situation in a final repository with canisters deposited in rock of low hydraulic conductivity and with a "respect distance" to the nearest major water-bearing zone will be simulated in the investigation. The results of the study will be evaluated and used to validate transport models on a block scale, ie over distances on the order of 10–100 m. The investigation will also demonstrate our ability to characterize and select volumes of sound rock for deposition. Transport models will be used to test the possibility of predicting the migration of dissolved substances in a selected volume of low-conductivity rock adjacent to a fracture zone. The goals of the investigation are therefore to:

- study the transport of solutes in the rock over distances of 10–100 m,
- validate models for transport in sound rock to a fracture zone,
- validate models for transport in a fracture zone.

The study is of great importance for the three main goals of the hard rock laboratory: "To test the quality and usefulness of methods for rock characterization", "To further develop and demonstrate methods for design, planning and construction" and "To collect material and data for the safety assessment". The block-scale tracer tests are primarily of great importance for the stage goal "Test models for groundwater flow and solutes". This modelling is of central importance for the assessment of the long-term safety of the final repository that will be submitted together with the siting application.

**Radionuclide migration** will be carried out to test the dissolution and migration of radionuclides in situ. Previous investigations have shown that solubility, sorption on fracture faces and diffusion into the rock matrix reduce the transport of radionuclides in the bedrock. The data and the models that describe the chemical properties of the radionuclides in the natural bedrock environment are based mainly on laboratory tests and the following experimental conditions are very difficult to simulate in the laboratory, however:

- natural reducing conditions,
- natural content of colloidal particles,
- undisturbed rock, ie rock with micropore systems and even large fractures that have not been depressurized through sampling.

All of these conditions are of extremely great importance for the rock as a barrier, ie they have a great influence on the solubility or retention of radionuclides if radioactive waste is exposed to groundwater. The goals of the radionuclide migration tests are to:

- test the dissolution and migration of radionuclides in situ,
- test the influence of natural reducing conditions on the solubility and sorption of radionuclides,
- test the ability of the groundwater to dissolve and transport radionuclides with natural colloids and microbes, humic substances and fulvic acids,
- validate models and check constants that are used to describe radionuclide dissolution in groundwater, sorption on mineral surfaces, diffusion in the rock matrix, transport in an individual rock fracture and radiolysis.

The goals are of great importance for the third main goal of the activities in the hard rock laboratory, namely to "Collect material and data for the safety assessment". The outcome of the tests is not likely to influence the siting of the final repository. The tests are of very great importance as a basis for the analysis of the transport of substances dissolved in water and thereby for the assessment of the long-term safety of the repository. An account of this will be submitted together with the siting application.

**Block-scale redox tests** will be carried out to demonstrate that the redox capacity of the rock is sufficient in the flow paths. Reducing conditions at repository depth are a necessary requirement for long canister life. The groundwater that has been sampled on different occasions and on different sites within the study-site investigations is always reducing, which proves the reducing properties of the rock. The kinetics of the redox reactions between the minerals in the bedrock and the groundwater require further study, however. During the construction phase, when oxidizing water will get down into the facility, there will be opportunities to study these reactions. The investigation of the effect of the oxygenated water will be carried out on a block scale (several tens of metres), enabling all relevant parameters to be checked and providing an opportunity for an assessment of the rate of the exchange reactions. The goal of the investigation is to determine the reaction kinetics when oxidizing water is transformed into reducing water by correlating flow rate with mineralogical changes.

The investigation is closely linked to the main goal to "Collect material and data for the safety assessment".

**Methodology for repository construction** is aimed at demonstrating how the construction of a repository is to be accomplished. In connection with the construction of a repository, it is necessary to carry out a number of investigations to obtain a final basis for the design and layout of the repository and sealing of the repository, and to obtain data for the final safety assessment of the completed repository. The execution of the investigations is dependent on the choice of system for the final repository. However, the following description is based on the assumption that a final repository is constructed at a depth of about 500 m and is designed in accordance with the KBS-3 method. It mainly describes the characterization required for the repository's near field. According to KBS-3, the near field is defined as "the area around the canister where the repository and its components directly affect the dispersal of nuclides that occurs when the canister has been penetrated. The effect can be of a chemical, hydrological or mechanical nature. The extent of the near field varies in time and cannot be specified exactly but can in practice be considered to extend up to a dozen or so metres from the canister". Extensive experience has been obtained from previous SKB studies regarding instruments and methods for characterization of the near field. This experience especially consists of results from the joint research in the Stripa project (radar, seismics and hydraulic measurements etc). Experience from the investigations of the study sites has also improved our ability to characterize the near field. Furthermore, tunnelling work in Sweden and abroad has provided a great deal of practical experience. In spite of the above experience, a complete demonstration of how the characterization of the near field in a final repository is carried out is lacking. The goal of "Methodology for repository construction" is to demonstrate on a natural scale how characterization of the near field can be carried out in a final repository designed according to the KBS-3 concept. The investigation can be divided into the following sub-goals:

- Develop a strategy for characterization of the near field.
- Demonstrate in an appropriately selected rock volume how the characterization is to be carried out.
- Show how flexibility can be achieved in a repository system, ie adaptation of deposition tunnels and deposition holes to the properties of the rock.

Another purpose of the investigation is to characterize the rock volume where the investigation described in Appendix C7 "Pilot tests, repository systems" will be carried out. In addition to a methodology for characterizing the near field, methods for tunnelling, boring of canister holes, injection grouting etc are needed. These needs are identified but the execution of the work has not been planned. It is foreseen that such planning will be carried out later. However, the above tests cannot be carried out before the principles for the design of a repository have been finalized in the mid-90s. For natural reasons, the investigation is closely linked to the main goals of the hard rock laboratory as well as to the stage goal "To demonstrate construction and handling methods".

**Pilot tests, repository systems** is a series of pilot and demonstration tests to be carried out after the main principles of repository design and systems have been finalized in the mid-90s. The goal of the tests is to validate the models and demonstrate the function of the systems by clarifying the interaction between the rock and the selected buffers under conditions prevailing in disposal facilities. A further purpose is to develop and test methods and strategies for their application. The pilot tests are closely linked to the main goal "To further develop and demonstrate methods for design, planning and construction" and to the stage goals "To demonstrate construction and handling methods" and "To test important parts of the repository system".

The test gives basic data for the building license application.

# A PROGRAMME FOR THE PRE-INVESTIGATION PHASE

Investigations of the bedrock are to be carried out during the pre-investigation phase. These are to be conducted both from the ground surface and in boreholes. Data are to be compiled in conceptual models as a basis for siting, facility layout and numerical calculations of groundwater flow.

The preliminary investigation phase is divided into three stages: Siting, Site description and Predictions. Two stages have been completed and the results reported and the final stage is underway (Sept 1989). During the Prediction stage, a thorough description of rock conditions is being prepared. Movements of the groundwater are being described under natural conditions and a forecast is being prepared for the disturbed conditions that prevail during the construction phase. Similarly, a tectonic description of the bedrock is being carried out. On the basis of the surveys that have been completed, SKB has decided to site the Hard Rock Laboratory on Äspö in the municipality of Oskarshamn.

Two basic facility alternatives have been studied. The evaluation has shown that a tunnel layout is preferable to a shaft layout. Tunnelling will take place to a depth of about 500 m.

## A 1 GOALS

The preliminary investigation phase has been conducted with the following stage goals:

- Collect the geoscientific data required to evaluate whether it is possible to locate the Hard Rock Laboratory around Simpevarp and to evaluate the need for detailed investigations for validation during 1988.
- Establish the basic data required for the preliminary facility layout of the hard rock laboratory.
- Establish programmes for shaft sinking/tunnelling and monitoring by 1989.
- Prepare a prediction for the geohydrological and geochemical changes that will occur in connection with construction of the research laboratory by 1990.

For the subject areas included in the pre-investigation phase, these activities have been conducted with the following subgoals:

### Geology

The goal is to describe the composition and heterogeneity of a given selected rock volume. This includes a precise description of the special distribution of rock types, large and small fracture zones and the fracture geometry and minerals of the rock mass.

The goal is further to describe the changes that can take place in the rock volume under the influence of temperature changes and geological processes, for example glaciations and tectonic processes. This goal is not bound to the pre-investigation phase.

### Geohydrology

The goal of the investigations is to describe the natural groundwater distribution and flow in a selected rock volume. Of particular interest is to describe the geometric distribution of the groundwater flow in the rock volume and quantify transmissivity and pressure head in these volumes, zones or fractures.

A further goal of the investigations is to supply the data necessary for setting up mathematical groundwater models for a selected rock volume. The models shall be devised in such a manner that they are able to describe with good accuracy the natural groundwater situation and the changes that take place in the ambient groundwater head and flow when a tunnel or shaft is excavated in the selected rock volume.

### Chemistry

The goal of the chemical investigations is to describe the ambient chemical composition of the groundwater and the fracture mineral and their distribution in different portions of the rock. The composition of the water in the low-conductivity portions of the rock is of particular interest. A subgoal is to describe and model the changes that take place in the groundwater's main components, trace-quantity components (especially of redox-sensitive constituents), content of natural isotopes, possible drilling water markers and tracers.

### Instruments

The goal is to make sure that suitable instruments are available for the different field investigations. Existing SKB instruments shall be used wherever possible and shall be modified or further developed where necessary. The instruments shall have high availability so that they do not hamper the execution of the measurements. Furthermore, suitable equipment shall be procured for the more or less permanent installations for long-term recordings.

### Construction Activities

Underground galleries for geoscientific studies and other experiments of interest for repository layout and safety assessment shall be excavated at a depth of about 500 m. The necessary buildings, accesses and auxiliary systems shall be built in the rock and at ground level. Tunnels and raises in the bedrock shall be designed in such a manner that fracture zones and homogeneous rock mass can be studied at different depths. Undisturbed groundwater, in equilibrium with a homogeneous rock mass, shall be available for investigations. Rock mapping, probe drilling and measurement and sampling in boreholes shall be able to be carried out during the construction period.

The method for excavation of an access to a depth of 500 m with simultaneous investigation of the rock mass and the groundwater situation shall be planned and developed in time for the future construction of the final repository.

## A 2 EXECUTION

The pre-investigation phase is being carried out as a project with a project leader and principal investigators for geology, geohydrology, chemistry, instruments, field work and construction work. For planning of the work, there is a Programme Group that compiles the programme with the help of the principal investigators. A special reference group reviews the programme and the results.

With the programme as a basis, Object Plans are defined by the principal investigators. The objects are purchased by SKB. Results are then reported in English in Progress Reports. These Progress Reports are evaluated and summarized by the principal investigators for geology, geohydrology and chemistry. The evaluation is presented in SKB's series of Technical Reports for each stage in the preliminary investigation phase.

The evaluation of the investigations carried out during 1986 and 1987 was presented in SKB TR 88-16. The report describes work done before core drilling of investigation holes was begun.

SKB TR 89-16 presents an evaluation of the investigation results and calculations carried out for the most part during 1988. It includes the results obtained from four cored holes, total length 3109 m. It also includes a comparison with the descriptions submitted in SKB TR 88-16.

The last planned drilling stage during the preliminary investigation phase was begun during the winter of 1988/1989. These results will be presented in 1990.

## A 3 INVESTIGATIONS FOR SITING AND PRIOR TO THE CONSTRUCTION PHASE

As a basis for siting and for future studies, investigations have been carried out on a number of different scales, both regionally and locally. Investigations were focussed almost immediately on a siting near Simpevarp, which, with its infrastructure, offers particularly good prospects.

The investigations for the Hard Rock Laboratory in the Simpevarp area were commenced in the autumn of 1986 with airborne geophysical surveys over an area of 825 $km^2$. Gravimetric surveys were carried out with a density of around one station per $km^2$. Preliminary geophysical ground profiles supplemented the airborne geophysical survey on the islands of Ävrö and Äspö and in the Laxemar area. Lineaments in the Simpevarp area have been interpreted on the basis of digital terrain models and compared with the topographical picture of aeromagnetic lineaments. The rock mass has been mapped on a scale of 1:10 000 in an area immediately surrounding Simpevarp and on a scale of 1:50 000 in a larger area.

The regional-scale rock description shows that the Simpevarp area consists primarily of granitic bedrock (Småland granite) with intrusions of basic rock types, greenstones. The information from the geological and geophysical surveys shows a tectonic picture of the Simpevarp area dominated by a nearly orthogonal system of first-order fracture zones in the N-S and E-W directions. Aside from this system, there are second-order zones running in the NW and NE directions that also form a nearly orthogonal system. There are probably also flat, subhorizontal zones. At present there is no evidence that such zones dominate the area around Äspö. Of importance for geohydrological models has been the fact that the Simpevarp area is surrounded by younger, granitic diapirs which have also been assumed to underlie the Simpevarp area at great depth.

The local-scale rock description has been concentrated to the Laxemar area and Äspö, where more detailed investigations have been carried out. The geohydrological investigations in the first stage included analyses of well data and hydraulic tests in percussion boreholes. In a second phase, four cored holes have been drilled, the deepest to a depth of 1000 m. Besides high quality core mapping, extensive geophysical measurements, have been carried out, along with hydro tests to several scales and hydrochemical analyses. Thorough surface investigations have been carried out on Äspö, including seismic profiles, outcrop mapping, geophysical measurements and cross-hole interference tests. The results of the investigations have shown that suitable sites for the Hard Rock Laboratory should exist both on Äspö and in the Laxemar area. Äspö can be divided into three geological units: the north block, the south block and in between a wide shear zone with intrusions of mylonite. The zone – called the Mylonite Zone – is oriented ENE-NE. Judging from the cored hole drilled on southern Äspö, Småland granite is the dominant rock type. Some crush zones can be expected down to a depth of 300 m, where the rock mass changes into a quartz-poor variety of Småland granite called diorite, which appears to be considerably less pervious

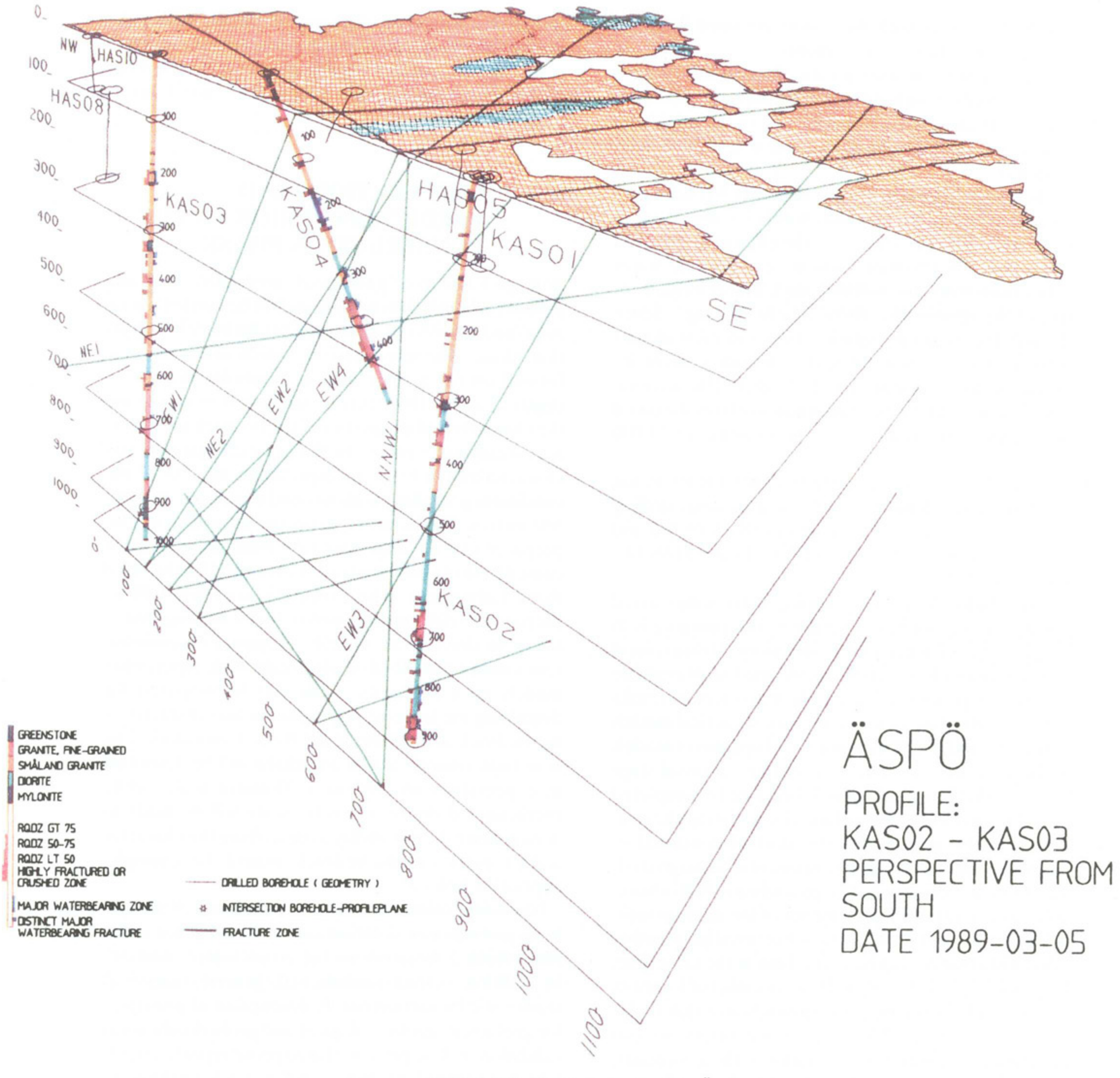


*Figure A-1. Important zones on Äspö.*

than the overlying rock. The fracture zones have been revealed for the most part by hydraulic cross-hole measurements and reflection seismics.

Southern Äspö has been proposed as a site for the hard rock laboratory. The investigation results have been presented in SKB TR 89-16, from which the following is summarized:

From the ground surface down to a depth of 315 m, the main rock type is a Småland granite. Below 315 m, diorite is the most common rock. There are several zones of different character on Äspö, Figure A-1. The central shear zone has a northeasterly direction with a northerly dip. NE 1 is estimated to dip 30° towards the NNW. EW 2 and 3 are eastwesterly with a presumed dip of 70° towards the north (EW 2) and almost vertical (EW 3). Zone NNW 1 is estimated to dip between 55° towards the east and vertically. This zone is judged to be an important hydraulic conductor. Narrow vertical zones and sub-horizontal zones also have to be taken into account. Reflection seismic surveys have indicated possible sub-horizontal zones at a depth of 300 – 500 m and 950 – 1150 m. They are characterized as being fairly short and non-interconnected. They could possibly be attributed to the contact between granite and diorite, which also agrees with the results obtained from the transient cross-hole measurements.

The hydraulic measurements of conductivity have been performed with different distances between the packers. Hydraulic conductivity and its variation as a function of rock type and measurement scale have been analyzed.

Chemical sampling of the groundwater has been performed in wells, in percussion boreholes and in cored holes. Of particular interest is the chloride content of the water. The chloride content of the saline water varies from 3000 mg/l to 11000 mg/l. The chloride content of the surrounding Baltic Sea is 3000 mg/l. Seven thousand years ago the salinity of the water was around 9000 mg/l. In the boreholes, the chloride content increases with increasing borehole depth, but the increase is not linear. C-14 dating of groundwater from the cored hole KAS 02 yields an age of the saltwater of 13 000 years.

The site description provided in SKB TR 89-16 has since been supplemented with an additional drilling stage consisting of four cored holes (KAS 05-08) and two new percussion boreholes (HAS 13 and HAS 14), see Figure A-2.

A concluding long-term pumping test is being carried out during the summer. The aim of the pumping is to simulate the influence of the laboratory. Measurement of groundwater head is being performed at all available observation points in the area. The measurement results will be used to fine-tune preliminary numerical models of the area and to calibrate improved updates of models of the area. Before pumping is started, an initial stage of the predictive modelling will therefore be completed first. The investigations include documenting the conditions in the area before the start of construction. Among the parameters to be documented is the groundwater flux at great depth. The groundwater flux in boreholes will be carried out by means of the dilution technique. A prerequisite is that no other investigations that cause disturbances can be carried out at the same time. In the initial predictive modelling, a number of forecasts will be made concerning the groundwater flux under ambient conditions. The dilution measurements can therefore be regarded as a validation of these forecasts. A qualified tracer test will be carried out before the start of the construction phase to provide further information on the groundwater's flow paths.

A summary of completed and planned investigations is presented in Table A-1.

The investigations completed so far show that Äspö fulfils the conditions for scientific experiments of great interest for a safe final repository. Furthermore, Äspö also fulfils the conditions for the qualified construction project to be carried out with good results. With a view towards future tests, it is an advantage if different types of rock and zones can be studied in the hard rock laboratory. This variation exists on Äspö with environs.

The geohydrochemical conditions on Äspö are also representative of this prevailing in an underground facility on a coastal site. The groundwater is fresh in the nearsurface zone and saline at greater depth. Furthermore, the site permits experiments to be carried out during the construction phase with good interpretability.

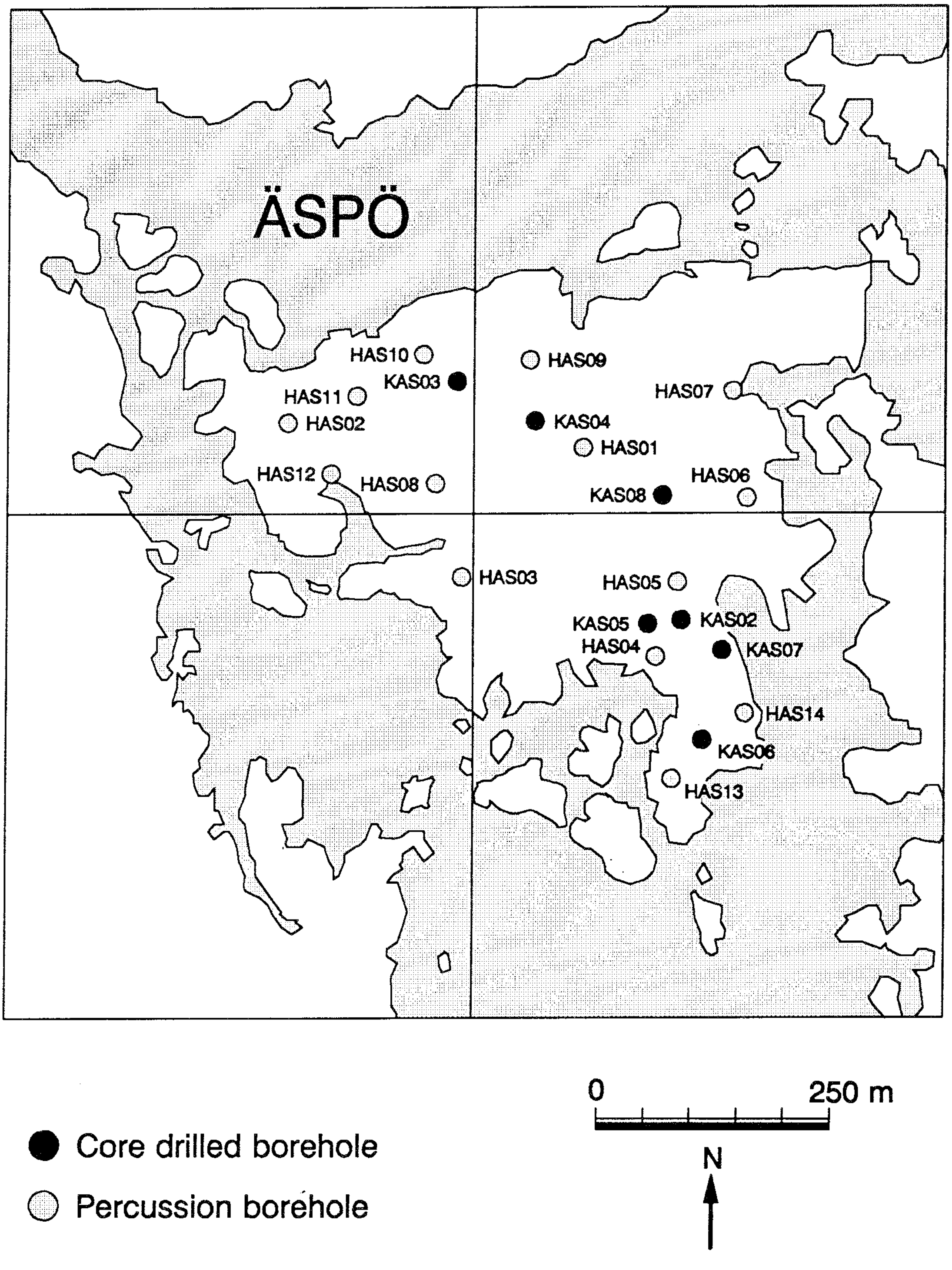
## A 4 CALCULATIONS AND PREDICTIONS PRIOR TO THE CONSTRUCTION PHASE

A large number of geological, geohydrological and geohydrochemical investigations will be carried out on Äspö and its environs during the preliminary investigation phase. The investigations, which are being performed on the surface and in boreholes down to a depth of about 1000 metres, are aimed at describing the character and properties of the bedrock in the current steady-state phase. In the preinvestigations, this characterization leads to expectation models of the conditions prevailing underground to a depth of about 500 metres. Furthermore, expectation models will be prepared of the changes that take place in the bedrock caused by the tunnels and raises excavated for the Hard Rock Laboratory. The expectation models will be prepared to different geometric scales varying from a km scale down to an m scale. Regional transmissive zones will be described on a km scale while expectation models on a 500-metre scale will be prepared for describing the large-scale properties and character of the bedrock around the Hard Rock Laboratory. The near field around tunnels and shafts will be described in expectation models on a 50-metre scale, while predictions down to a 5-metre scale will be made to demonstrate the possibility of describing the character and properties of the bedrock around, for example, deposition holes.

Numerical calculations will be conducted of the ambient groundwater situation and of the influence of the Hard Rock Laboratory on the groundwater situation. In addition, certain fundamental, generic, numerical studies will be carried out. A description of principles for geological, geohydrological and geohydrochemical validations will be presented in a special report currently being prepared. Predictions will be made on different scales:

- regional scale, > > 1000 m,
- facility scale, 100 – 1000 m,
- block scale, 10 – 100 m,
- detail scale, 0 – 10 m.

The predictions to be made, a qualitative/quantitative estimation of the expected outcome, basis for validation and the measurement accuracy striven for shall be defined for each scale. The predictions for each scale will be grouped according to research areas and will lead to a testing of conceptual models, groundwater flux, chemical environment, transport of solutes in



SKB Swedish Hard Rock Laboratory

*Figure A-2. Boreholes on Äspö.*

groundwater and mechanical stability of the rock during the construction period.

Calculations will be compared before the construction phase begins with head and flow measurements in boreholes and with hydrochemical data, especially on the salinity of the water. During the construction phase, the geological, hydrological and hydrochemical predictions made during the prediction stage will be evaluated. Theoretical and predictive numerical modellings in particular are described in the following.

Numerical modelling involves a number of steps. The nomenclature for these steps will be clearly defined in

Table A-1. **Completed and planned investigations during the preliminary investigation phase.**

| ACTIVITY | REPORTS | | |
|---|---|---|---|
| | **SKB TR 88-16** | **SKB TR 89-16** | **To be printed in 1990** |
| GEOLOGY | | | |
| Airborne geophysics | ● | | |
| Gravimetry | ● | | |
| Lineament studies | ● | | |
| Rock mapping | ● | ● | ● |
| Fracture mapping | ● | ● | ● |
| Tectonics | ● | ● | ● |
| Petrophysics | ● | ● | ● |
| Ground geophysics | ● | ● | ● |
| Refraction seismics | ● | ● | |
| Reflection seismics | | ● | |
| Percussion drilling, logging | | | |
| – HAS 01-07, HAV 01-08, HLX 01-07 | ● | | |
| – HAS 08-12, HLX 01-07 | | ● | |
| – HAS 13-15 | | | ● |
| Core drilling, mapping, logging | | | |
| – KAS 02-04, KLX 01 | | ● | |
| – KAS 05-08 | | | ● |
| Rock stresses | | ● | |
| Rock mechanics | | | ● |
| **GEOHYDROLOGY** | | | |
| Analysis of regional well data | ● | | |
| Compilation of geohyrological data from construction work | ● | | |
| Hydrology | ● | | |
| Pumpt tests in percussion boreholes | | | |
| – HAS 01-08, HLX 01-07, HAV 01-08 | ● | | |
| Hydraulic tests in cored holes | | | |
| – KAS 02-04 | | ● | |
| – KAS 05-08 | | | ● |
| Cross-hole tests | | | |
| – KAS 02, KAS 04 | | ● | |
| – KAS 05-08 | | | ● |
| Flow measurements in boreholes | | | ● |
| Long-term pumping, LTP | | | ● |
| Numerical models | | | |
| – generic drawdown | ● | | |
| – 2D regional | | ● | |
| – 3D regional | | ● | |
| – interface fresh/saline water | | ● | |
| – 3D facility scale | | | ● |
| – Prediction of LTP | | | ● |
| – Drawdown calculation | | | ● |
| – Network model | | | ● |

**(Cont.)**

**Table A-1. Completed and planned investigations during the preliminary investigation phase. (Cont.)**

| ACTIVITY | REPORTS | | |
|---|---|---|---|
| | SKB TR 88-16 | SKB TR 89-16 | To be printed in 1990 |
| **GROUNDWATER CHEMISTRY** | | | |
| Analysis of regional well data | ● | | |
| Superficial groundwater chemistry | ● | | |
| Detailed characterization of groundwater<br>– KAS 02-04, KLX 01 | | ● | |
| Characterization of Radium and Radon in surface water | | | ● |
| Deep groundwaters on Äspö and Laxemar groundwater KAS 05-08 | | | ● |
| Tracer tests during LTP | | | ● |
| Predictive modelling of tracer tests during LTP | | | ● |
| **DESCRIPTIVE MODELS OF GEOLOGY, GEOHYDROLOGY AND GROUNDWATER CHEMISTRY** | | | |
| – Regional scale | ● | | ● |
| – Facility scale | ● | ● | ● |
| – Block scale | ● | ● | ● |
| – Detail scale | | | ● |

a report that is under preparation. A preliminary account is provided in the following.

**Verification** is a checking procedure to check that a computer program as such performs calculations correctly on the physical problems that are to be solved. Verification of the programs takes place against exact analytical solutions and by comparison between different programs. In the future, it will be assumed that the programs that will be used in calculations for the Hard Rock Laboratory are documented and verified. In some cases, it may be necessary to perform verification checks as a part of the modelling work, for example check volume calculations of mass balance errors.

**Calibration** is a process where a (numerical) model is adjusted on the basis of quantities measured in the field. Data to calibrate against may be measured groundwater heads and flows. The measurements can be carried out under undisturbed conditions and under disturbed conditions in connection with tests. The fitness of the model can be measured in terms of an expected value for model deviation and its variance. Calibration is a more or less methodical process for minimizing the deviation and its variance. A calibrated model can thus be said to have a certain accuracy.

**Prediction** involves using a calibrated model for predictions about the future. The predictions may concern flows, groundwater heads and flow times, for example. Better accuracy cannot be expected of a forecast than is provided by the calibrated model. Limits shall be stipulated for the deviations and variance of the prediction.

**Validation** entails comparing a prediction with actual outcome in a systematic manner. The actual outcome can be natural conditions or some controlled disturbance. A forecast and validation criteria shall describe how, and against what data, validation is to be performed before the actual outcome is measured. Thus, in a validated model, the forecast is fulfilled with the pre-stipulated accuracy. Validation also includes a critical examination of underlying processes and a (subjective) judgement of whether the prediction is sufficiently good.

The first evaluation, TR 88-16, described a characterization of the bedrock to the regional scale, to the

Äspö scale and in several blocks with 50 m sides. The same report described how to calculate the drawdown for a shaft layout and a tunnel layout. The calculation was 3-dimensional and was carried out using analytical element technique. Material data are based on preliminary assumptions concerning the hydraulic conductivity of the rock and its and depth dependence. The groundwater flows are calculated with the rock's hydraulic conductivity as an independent variable. With assumed boundary conditions, the radius of influence is approximately 2 km for a facility at a depth of 500 m.

The regional description presented in TR 88-16 formed the background of a regional groundwater flow model and a theoretical study of the interface between fresh and saline water. These numerical studies have been reported in TR 89-16.

The regional numerical study was carried out in two and three dimensions using finite element technique. Pressure head and flow pattern were shown on a regional scale. In order to enable the boundary conditions to be defined on a subregional scale, the influence of the Hard Rock Laboratory was modelled. Hydraulic units in the two-dimensional model – 28 km long – were based on a gravimetric profile that showed rock type distribution with depth. Calculations were carried out for constant and decreasing conductivity with depth, with and without the Hard Rock Laboratory in place. The results showed that a three-dimensional model should have a horizontal extent of about 3 km around the Hard Rock Laboratory in order that the laboratory should not influence the boundaries.

A simple rock type classification was also utilized in the three-dimensional model. Two calculation cases were carried out – with and without the laboratory in place. Agreement between the pressure head pattern in the model and in reality is satisfactory. Calculations of flows and flow paths must be regarded as illustrations, however.

A theoretical study of the interface between fresh and saline water has been presented in TR 89-16. Water is present in the Äspö area with a salinity higher than that of the Baltic Sea and underlying fresh water. In the theoretical model, the flux and the location of the saline water interface are simulated in a two-dimensional finite difference model. The programme has been verified against published problems included in the HYDROCOIN project. The influence of horizontal and vertical structures has been investigated. The stability of the interface has also been investigated in the study for different assumptions of random variations in hydraulic conductivity. The conductivity has been assumed to be log-normally distributed. The influence of different variances on the material has been analyzed.

During the summer of 1989, a large pumping test will be carried out, as described above. This test will be preceded by predictive modelling. Before the start of pumping, the rate of inflow into the borehole and the drawdown at different observation points will be calculated. The work includes setting up a numerical model in 3D of southeast Äspö with environs, calibrating the model against geological, geophysical and geohydrological data and predicting the outcome during pumping. The model can be calibrated against measured groundwater levels from the area and measured flows and drawdowns from cross-hole measurements. The model shall be validated against measured drawdown data from the test pumping.

In the predictive modelling of the long-term pumping, flow path calculations from several selected points must be carried out for the purpose of orientation. These points can be regarded as points of admission for tracers in a tracer test that will be carried out separately in the spring of 1990.

The tracer test will also be predicted. The transport modelling includes a predictive part, represented by flow path calculations, where predictions are made of where tracers injected at different points will enter the pump hole. This part can be validated against data from the tracer test. The modelling also includes a calibration part, where breakthrough curves from the tracer test are used to calibrate transport and dispersal parameters for the detected flow paths. The results of tracer test will serve as a basis for planning the tracer tests during the construction phase.

Modelling of the long-term pumping and the tracer test will be done both with the finite element method, where the rock is regarded as a heterogeneous continuum, and with the finite difference method. The latter model is a sitespecific continuation of the theoretical studies of the interface between fresh and saline water. For this model, a number of lithological and structural units will be defined and assigned a conductivity distribution for a stochastic continuum. In order to check the stability of the models, simulations will then be carried out with different generated stochastic fields and with increasing variance.

A numerical model of the laboratory and its near field during different stages of its construction comprises an important part of the site-specific expectation model. This model can be regarded as a direct continuation of the aforementioned studies for the pumping test. The model shall be set up with the geometry for the laboratory that follows from the design documents. The calculations will be carried out either with finite element technique or differential technique. For the inflow calculations, the presence of a skin zone of lower permeability immediately adjacent to the access tunnel will be assumed. Inflow and drawdown will be calculated for different stages of access tunnel construction. The model will be calibrated against measured groundwater levels, hydraulic measurements and the long-term pumping. The forecast will be validated against the actual course of events during the construction phase, see further Appendix B3.

A problem of a slightly different nature is that of devising models for how the flow is distributed under natural conditions at laboratory depth. The problem is of importance for calculating the bypass flow around deposited waste. The modelling will be done with a network model that takes into account the individual fractures and will be applied on the block scale with a side length of 50 m. The point of departure is the geological-tectonic picture described in TR 89-16 and the work carried out during the summer of 1989 to correlate geology and geophysics with conductive structures. Base data in the form of fracture mappings and co-evaluated hydraulic measurements will be available. The modelling is done as a calculation of the flow distribution around emplaced canisters. The gradients obtained from calculations using regional and facility-specific models under undisturbed conditions will be used as a driving force for the flow.

The model will be evaluated during the preliminary investigation phase against dilution measurements performed after the long-term pumping and up until the start of construction.

## A 5 DESIGN OF THE LABORATORY

Alternative designs of the underground part of the laboratory were studied in 1987. The results showed that a tunnel ramp was preferable to the sinking of a shaft. The tunnel alternative provides greater opportunities for collection of data and characterization of the rock mass, in accordance with one of the main goals of the research programme. The comparison between tunnel and shaft was made on four different grounds:

### Collection of data and characterization of the rock

Opportunities for collection of data and characterization of the rock mass are considerably greater in a tunnel alternative. Owing to its size, a tunnel will cut through a considerably larger rock mass than a shaft. This provides a much better opportunity to check the completeness of the pre-investigations. It is vital that the flow paths be located to permit valid calculations to be carried out, and in a later phase to permit tracer tests to be interpreted. The exposed surface area is greater in a tunnel than in a shaft. This provides greater opportunities for characterization of the three-dimensional fracture systems in the rock. Steeply dipping zones can be studied at one or more levels. It is also considerably simpler to arrange testing stations in a tunnel. As far as tracer tests are concerned, they are normally carried out from several injection points to a single detection and sampling point. A serious limitation with such tests is that they cannot be utilized to determine the transport to a point that cannot be monitored (with measuring instruments). In a tunnel, tracer tests can be performed to an arbitrary number of points along the entire tunnel. The detection points are then spread out in a relatively large volume of the rock. Tracers injected in surrounding holes are detected at breakthrough.

### Methods and knowledge for numerical modelling and validation of calculations

A shaft alternative is easier to model numerically. It is, however, urgent that calculation models be developed, since a future repository may have a complex geometry with regard to both the storage galleries and the entrance. A shaft alternative also involves a relatively complex geometry if account is taken of ventilation raise, intermediate levels etc. Calculations are validated by, for example, measuring the inflow into the facility. Both alternatives provides opportunities for this, but the measurement is more complex in the shaft alternative. The alternatives are judged to be equal.

### Time schedule, method development and costs for investigations and construction

The tunnel alternative influences the groundwater situation in a larger area, as a result of which the amount of investigation work required will be greater during both the pre-investigation and the construction phases. The time schedule and construction cost are more advantageous for a tunnel alternative down to 500 m. At 500 m, the difference between the alternatives lies within the margin of error. Entrance to a repository can be provided through a tunnel or shaft. In the USA's waste management programme, for example, the entrance to the planned repository is provided through a tunnel. This may also be preferable for a Swedish final repository. A tunnel provides much greater flexibility in investigations and construction. The tunnel and shaft alternatives are judged equal.

### Operation of the facility

Personnel transport is assumed to take place in both cases via elevator. For transport of material, a tunnel is preferable. Ventilation and drainage will be cheaper for a shaft alternative, however. For future scope of works, a tunnel provides great flexibility in establishing testing stations in different types of rock and fracture zones. Tunnelling can also be utilized to build up the knowledge required for using a tunnel as a means to characterize the near field. In future tracer tests, it is important that the rock be thoroughly characterized and that the boundary conditions be under control. These requirements are the same for the tunnel and shaft alternatives, but should be easier to fulfil in a tunnel alternative. In the case of a final repository, it is assumed that horizontal tunnels will be built. It is urgent that methods for characterization and progressive rock adaptation be developed and tested in the Hard Rock Laboratory. Thus, research needs and simple communications with the surface speak in favour of a tunnel.

In August 1989 the government decided that the Hard Rock Laboratory should be reviewed under the Act on the Conservation of Natural Resources. In connection herewith SKB has decided to make certain changes in the layout of the laboratory which will reduce the environmental impact. In the new layout the entrance tunnel is located on the Simpevarp peninsula instead of on Äspö as was earlier planned.

# B PROGRAMME FOR THE CONSTRUCTION PHASE – CHARACTERIZATION OF THE BEDROCK AND VALIDATION OF EXPECTATION MODELS

## B 1 GENERAL

During the pre-investigation phase, a large number of geological, hydrological and hydrochemical investigations will be carried out on Äspö and in its environs. The investigations, which will be performed on the surface and in boreholes down to a depth of about 1000 metres, are aimed at describing the character and properties of the bedrock in the current steady-state phase. In the final phase of the pre-investigations, expectation models of the conditions prevailing below the surface down to a depth of about 500 metres will be compiled. Furthermore, expectation models will be prepared of the changes that take place in the bedrock caused by the tunnels and shafts excavated for the hard rock laboratory.

During the construction phase, investigations will be carried out to validate expectation models and to provide data for progressive improvement of previous predictions. The investigations will be carried out both along the surfaces of the access tunnel and in boreholes from the ground surface and from the tunnel. Since favourable properties of the bedrock nearest the deposition holes and deposition tunnels are of the greatest importance for the safety of a final repository, it is essential that the degree of detail in the investigations during the construction phase be gradually increased. Investigations on the future main level, about 500 m below the surface, will be more detailed than in the beginning of the tunnelling work. Investigations during the tunnelling work are therefore divided into stages as follows:

Stage 1 – Excavation of the access tunnel to a depth of about 350 m, where the tunnel is expected to pass through the granitic rock and enter the dioritic. At this level, a pause of up to six months will be made to compile and evaluate the measurement data and other results. These results will provide a basis for an updating of the expectation models for the deeper-lying parts of the underground laboratory. At the same time, an evaluation of strategy and measuring methods used for the investigations completed down to a depth of about 350 m will be carried out. Raise boring to the surface from to a depth of about 350 m and in close connection to the access tunnel will also be carried out during this stage.

Stage 2 – Excavation of the tunnel down to a depth of about 500 m. The investigations along this stretch will be more detailed than the previous ones to permit a better description of the near field around the access tunnel. At a depth of about 500 m, tunnelling will be interrupted and the obtained results compiled, evaluated and compared with previous expectation models. The collected

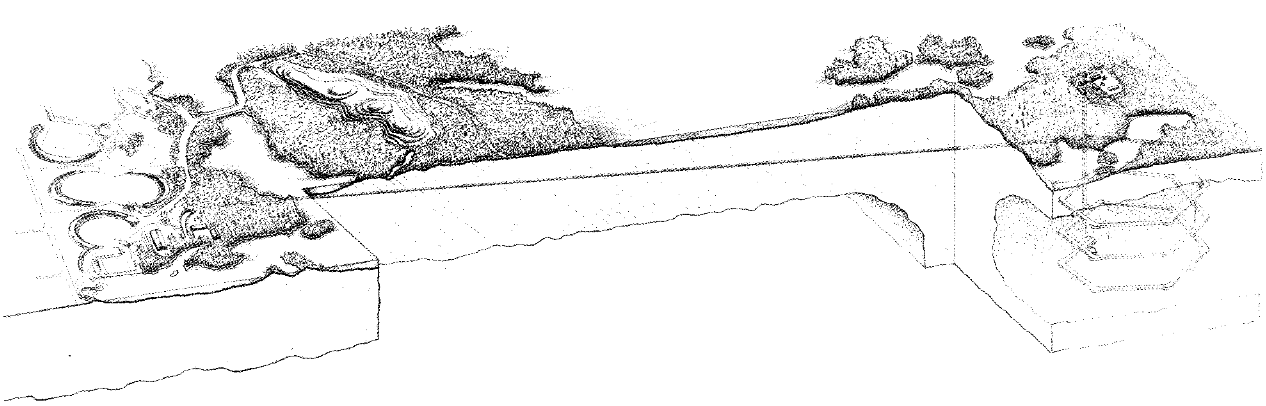


*Figure B-1. Tunnels and raises in the Hard Rock Laboratory.*

data will once again provide a basis for a further improved expectation model of the operating area, at the same time as the investigation strategy and measuring methods will be evaluated. The stage will conclude with characterization of the testing stations for some of the tests to be carried out during the operating phase and continued raise boring to a depth of about 500 m.

If later investigations within the framework of the general research programme should show that the final repository should be situated deeper that about 500 m, a further extension of the laboratory to greater depth may be considered.

A brief description of geological, geohydrological and geohydrochemical work during the construction phase is provided below.

The scheduling and planning of the investigations have been based on the following assumptions:

- Work on the access tunnel will begin in 1990. The cross-sectional area will be around 25 $m^2$. The work will be done in two shifts with time off for holidays and vacations.
- The sides of each hexagonal turn of the tunnel spiral will be about 135 m long. Each turn of the spiral will contain 810 m of tunnel length. For detailed investigations of fracture zones, among other things, eight side tunnels will be cut with a cross-sectional area of about 20 $m^2$ (free height at least 3.5 metres) along the access tunnel, see Figure B-1. The side tunnels, which are assumed to have a length of about 40 metres, will be cut by means of controlled blasting. Each turn of the spiral (including two side tunnels per turn) is estimated to take about six months. The length of the access tunnel down to a depth of about 500 metres will be about 3250 metres, and the total length including the side tunnels will be just under 3600 metres.
- The gradient of the tunnel will be such that each turn of the spiral will result in a downward movement of about 120 metres. With an estimated start during August 1990 and time off for vacations and holidays, the tunnelling should have reached about the 350-metre level by April 1992. Following a break of about six months, tunnelling will continue according to the above assumptions and will have reached about the 500-metre level by the end of 1992.
- In parallel with the tunnelling work, a raise for ventilation, electricity, emergency evacuation etc will be excavated as an additional connection between the bottom level and the ground surface. The raise will have a cross-sectional area of about 10 $m^2$ and will also have a connection with the access tunnel at approximately the 120, 240 and 360 metre levels.
- During the second construction stage, tunnels will be for utilities and for the caverns that are required to carry out block-scale tracer tests, radionuclide migration tests and redox tests. It is assumed that the investigations will be carried out for the most part on about the 500 metre level, ie a single level. Including the time required for fitting out shafts and making other arrangements necessary for the operation of the laboratory, it is assumed that the construction phase will be completed by 1994.

The design of the 500 m level has not yet been determined in detail. It is foreseen that arrangements for the remaining tests will be completed in an additional construction stage around 1998.

An SKB TR-report that will present the results of the evaluation of the prediction made for the rock down to a depth of 350 m is planned for 1992. It will also discuss possible changes in the data collection methodology prior to construction stage 2. Furthermore, a TR-report will be submitted before 1993 with a prediction for the rock below the 350 m level, encompassing construction stages 2 and 3. This report will also describe how the methods for evaluation are to be modified.

## B 2 GEOLOGICAL INVESTIGATIONS

### B 2.1 Background and Current State of Knowledge

The rapid increase in construction of underground facilities in rock all over the world has led to a development of geophysical surveying methods in particular for investigation and description of the properties of the rock mass. The pre-investigations that are normally conducted in connection with the planning of tunnels and rock galleries are usually limited to roughly locating any major zones of weakness of importance for stability and hydraulic conductivity in a facility. These investigations more rarely provide a basis for a general characterization of the entire unperturbed rock mass. For natural reasons, no evaluation of preliminary investigation methods used and predictions made is normally carried out in connection with the construction of commercial underground rock facilities. A few research projects have reported results from conclusions of predictions, which are always based on limited pre-investigation data.

Moreover, the investigations are limited to a few of the questions that are of interest for a safe final repository. In addition, the pre-investigation methods that have been developed are for the most part designed to describe the relatively shallow parts of the bedrock (100–200 m) where most underground rock facilities are built. Finally, much of the experience from non-crystalline bedrock outside of Scandinavia is not directly applicable to conditions in the Swedish crystalline bedrock.

In summary, it can be concluded that a number of geological and geophysical methods are available to aid in describing the composition and structure of the rock mass. The relevance of the different methods, both in general and in the local geological environment, is incompletely documented, however. This is particularly true of conditions at great depth in crystalline bedrock.

The current state of geological knowledge with regard to Äspö is based on an extensive pre-investigation programme of which two stages have been completed and the third is in progress (1989). See Appendix A.

## B 2.2 Goals

The overall goals of the geological documentation during the construction phase can be summarized as follows:

- Evaluate to what extent the pre-investigation methodology used has provided a correct description of the spacial distribution of rock types, large and small fracture zones and the fracture geometry and minerals of the rock mass in different geological environments and at different depths.
- Establish the relevance of different investigation methods as regards rock types, structures, stability and hydraulic conductivity with respect to geological environment and depth.
- Prepare a good forecast for the geological environment that will be encountered during the second construction stage and during the construction of the operating level.
- Develop and test methodology for detailed geological investigations on candidate sites for a final repository.

The geological investigations during the construction phase are closely linked to the stage goals of the hard rock laboratory: "To verify pre-investigation methods" and "To establish detailed investigation methodology".

The investigations are of fundamental importance for testing, developing and demonstrating the methods and the technology required for the detailed site investigations. This applies in particular to:

- testing of the relevance of different geophysical methods at different depths in crystalline bedrock,
- testing of methodology for preparing expectation models of rock volumes on different scales with subsequent validation,
- test of the reliability of the expectation models.

The investigations are also of fundamental importance for the planning of tests to be carried out during the operating phase.

## B 2.3 Execution

Geological documentation of tunnels, shafts and drilling will be carried out continuously in connection with the construction of the facility. This presumes a smooth coordination between rock excavation and documentation. The endeavour will be to map the data that are most essential in the working face after each blasting round. In order to enable this to be done as quickly as possible, only lithological boundaries and major structures will be mapped. Their coordinates will be measured to permit direct storage in computers. Photographic documentation of the face will be carried out after each round. Supplementary mapping will be done on later occasions (holidays, vacations) when operations do not interfere. Tunnel mapping will be done with a field computer (Geomac or the like). All information will be stored in computers on location on Äspö for processing in CAD systems. Storage in a database will permit simple retrieval of information whose form, format and style can be adjusted. This form of presentation is a necessary prerequisite for effective evaluation. Data will be evaluated as the excavation and documentation work proceeds so that reporting can be done in connection with the relatively brief interruptions in tunnelling after each stage. Raises will be documented prior to installation.

The above applies primarily to Stage 1, ie the investigations down to a depth of about 350 metres. Experience from this first stage will be continuously compiled to permit modifications of the programme during the course of the investigations. In Stage 2 (down to a depth of about 500 metres), the degree of detail in the description of the geological conditions in the near field will increase as the distance to the 500 m decreases. Since the results obtained from the investigations down to the 350-metre level will largely determine the plan for continued activities, it is not necessary to describe this plan in any greater detail now.

## B 2.4 Predictions

The geological expectation models are to be concerned primarily with lithology and structures.

A description of which properties of the rock are to be predicted – qualitatively or quantitatively – is included in the "Validation Report" that will be published as a Progress Report. Predictions will be made in the following stages:

- Before the tunnelling work is begun, a prediction will be made for the entire rock volume.
- Before Stage 2 is begun, the prediction will be updated for the rock volume below the 350-metre level.
- Before blasting of the testing area is begun, the prediction will be further updated for the operating level at a depth of about 500 metres.

Predictions will be made on different block scales for different geological environments. The endeavour shall be to define different lithological units (percentage distribution of different rock types along the tunnel, or designated volumes) and to describe the structure of the rock mass with regard to orientation and character. This includes rock type contacts, fracture frequency, fracture zones and rock quality. Rock type contacts are to be predicted with respect to number and character. Character shall include the joint's imperviousness, degree of crushing and alteration, orientation and hydraulic conductivity. Fracture frequency shall include fracture sets, character, orientation, minerals and length. The fracture zone description shall include width, length, character, contacts, clay content and possibly also hydraulic conductivity. Rock quality will be described using a rock classification method.

### B 2.5 Evaluation

Evaluation will be done in close connection with documentation. All data from tunnel mapping and drilling as well as any geophysical investigations will be compiled in descriptive models that will be compared with previously prepared expectation models. The evaluation will be qualitative to a large extent, but quantitative parameters will be used wherever possible.

### B 2.6 Reporting of Results

The obtained results, comparisons with and updating of the expectation models and proposals for changes in investigation methodology will be presented during interruptions in the tunnelling work at a depth of about 350 metres and prior to blasting of the 500-metre level. This reporting of results will be integrated with the geohydrological and geohydrochemical investigations so that as complete a picture as possible is obtained of the character and properties of the bedrock.

### B 2.7 Construction Works

Special construction works are not judged to be necessary for the geological documentation. Supplementary investigations will be carried out from side tunnels and niches that have been blasted out for other purposes.

### B 2.8 Preparatory R&D

It is of great importance that the methodology to be used for the documentation work has been thoroughly tried and tested when the work starts. Since mapping is planned to be carried out in accordance with a partially new system, a testing period should be striven for in a tunnel under construction. Experience from the mining industry should also be utilized.

Preparatory R&D will start with the drawing-up of an object plan that describes in detail what is to be documented in the Hard Rock Laboratory, how the database is to be constructed, what practical methods are to be tested for data collection underground, how data are to be presented etc as well as a proposal for a pilot study to test the entire chain from data collection to reporting of collected data.

During the autumn of 1989, a pilot study will be carried out in a rock facility under construction, of which the results will be reported in the spring of 1990. This test shall include the following:

- Practical skills in the mapping work such as coordinate measurement, use of field computer etc.
- Storage of information. Digitization of data. CAD draughting.
- Presentation of data in a form that permits simplified evaluation (CAD program).

The pilot study shall also include defining how water seepage is to be mapped. The pilot study will form a basis for the detailed instructions and training to be commenced in the summer of 1990.

## B 3 GEOHYDROLOGICAL INVESTIGATIONS

### B 3.1 Background and Current State of Knowledge

During the pre-investigation phase, a large quantity of geohydrological data has been collected from surface and borehole investigations on Äspö with environs. The purpose of these investigations has been to determine current geohydrological conditions on Äspö and to describe, in expectation models on different scales, the influence of the hard rock laboratory on these conditions.

The pre-investigations have provided information on the current status and geometry of lithological and structural units in the investigated area. A large number of hydraulic measurements in and between boreholes have been carried out to determine the location, direction, extent and conductivity of good groundwater conductors in the bedrock. Groundwater level and head measurements have been carried out on Äspö as well as on Ävrö and Laxemar. These measurements will continue during the construction phase. Additional hydrological data have been obtained from a meterological station in Simpevarp. In addition, the results of the geohydrochemical investigations have provided a basis for the geohydrological characterization of the area.

Furthermore, a long-term pumping test has been carried out on Äspö (summer 1989) to simulate the influence of the hard rock laboratory on geohydrological conditions. Before this pumping, changes in head and flow were forecast in an expectation model.

The completed investigations have shown that favourable geohydrological conditions exist on Äspö for constructing a hard rock laboratory, of which the following can be mentioned:

- A homogeneous rock block with few well-defined groundwater-conducting structures exists on

southern Äspö, where the access tunnel to the laboratory can be built.
- Nearby the above, there is access to a central shear zone and areas with very homogeneous Småland granite.
- Areas below the surface of the sea are available immediately adjacent to Äspö.

## B 3.2 Goals

The overall goals of the geohydrological investigations during the construction phase can be summarized as follows:

- Evaluate to what extent the preliminary investigation methodology used has provided an accurate description of the natural groundwater situation in different geological environments and for different depths.
- Document the geohydrological conditions in the rock volume from tunnels and rock galleries on different scales and make geohydrological operating forecasts for the blasting work.
- Iteratively with the documentation, validate the different-scale models of the influence of the hard rock laboratory on the steady-state geohydrological conditions.
- With the new data continuously being gathered during the construction phase, progressively refine and improve the forecasts of geohydrological conditions at deeper levels.
- Validate the updated expectation models of geohydrological conditions at deeper levels, including the operating level.
- Develop methods for detailed geohydrological investigations on candidate sites.

In order to achieve these goals, it is necessary, as before, that investigations be carried out in the field, that the data obtained be analyzed and processed integrally with the geological and hydrogeochemical investigations, and that the results be integrated into qualitative and quantitative models. The investigations are of crucial importance for the description of the rock in both the far field and the near field. The work will, for example, provide information on where in tunnels and shafts groundwater seepage is expected to be abnormally high and where grouting measures are required to limit the seepage to an acceptable level. Furthermore, the disturbed zone around tunnels and shafts and its hydraulic properties shall be described both qualitatively and quantitatively. Finally, the investigations shall provide information on the possibility of concentrating the planned investigations during the operating phase on an appropriate and adequate rock quality.

The investigations are closely linked to the hard rock laboratory's stage goals: "To verify pre-investigation methods" and "To establish detailed investigation methodology".

## B 3.3 Execution

The most important steps included in the geohydrology programme during the construction phase are described below. This framework will be further refined so that a complete programme is established prior to the start of construction. Modifications in the programme may also be made during the construction phase on the basis of results obtained.

A geohydrological monitoring programme for continuous recording of such parameters as groundwater level and head in boreholes on Äspö was started in connection with the 1988 investigations. This work will be continued during the construction phase. In order to follow the impact caused by the excavation of the Hard Rock Laboratory, it may be necessary to perform additional drillings from the ground surface. As during the pre-investigations, it is important to have a reference area with a relatively fixed programme and a programme for the area around the laboratory that is revised regularly on the basis of the progress of the work.

During the blasting work, records will be kept of rock types, fracture content, reinforcing measures etc. These records will also include water seepages in terms of quantity and location. Water seepage into the tunnel will be measured by means of measuring weirs located at intervals of about 100 – 150 metres along the access tunnel. The measuring weirs will be designed in such a manner that seepage water from the tunnel sections between two weirs can be measured and sampled. This requires the installation of a pipeline running all the way through the access tunnel.

An action programme describing how the geohydrological observations are to be carried out in connection with injection grouting and extensive reinforcing work will be prepared. The programme will also define the limits for when injection grouting is to be done. It will also contain guidelines for when side tunnels are to be arranged.

Probe holes will be percussion-drilled from the tunnel sides at the tunnel face every 15 metres. The holes should be about 20 metres in length. Pressure buildup tests and, if required, packer seal measurements will be carried out in the holes, which will be drilled diagonally forward. These pilot investigations will be used to provide operating forecasts in combination with data from the tunnel and to supplement the database with geohydrological data collected underground. The boreholes will also be used for water sampling, see section B4.

In addition to the probe holes that are drilled regularly at the tunnel face, the observation network underground will be supplemented to characterize and measure the pressure in conductive zones. For this purpose, a total of about ten percussion boreholes 30 metres in length with multi-packer systems are expected to be required along the tunnel run.

To investigate, describe and model conductive zones without disturbing and being disturbed by the construction process, it is planned that approximately eight side

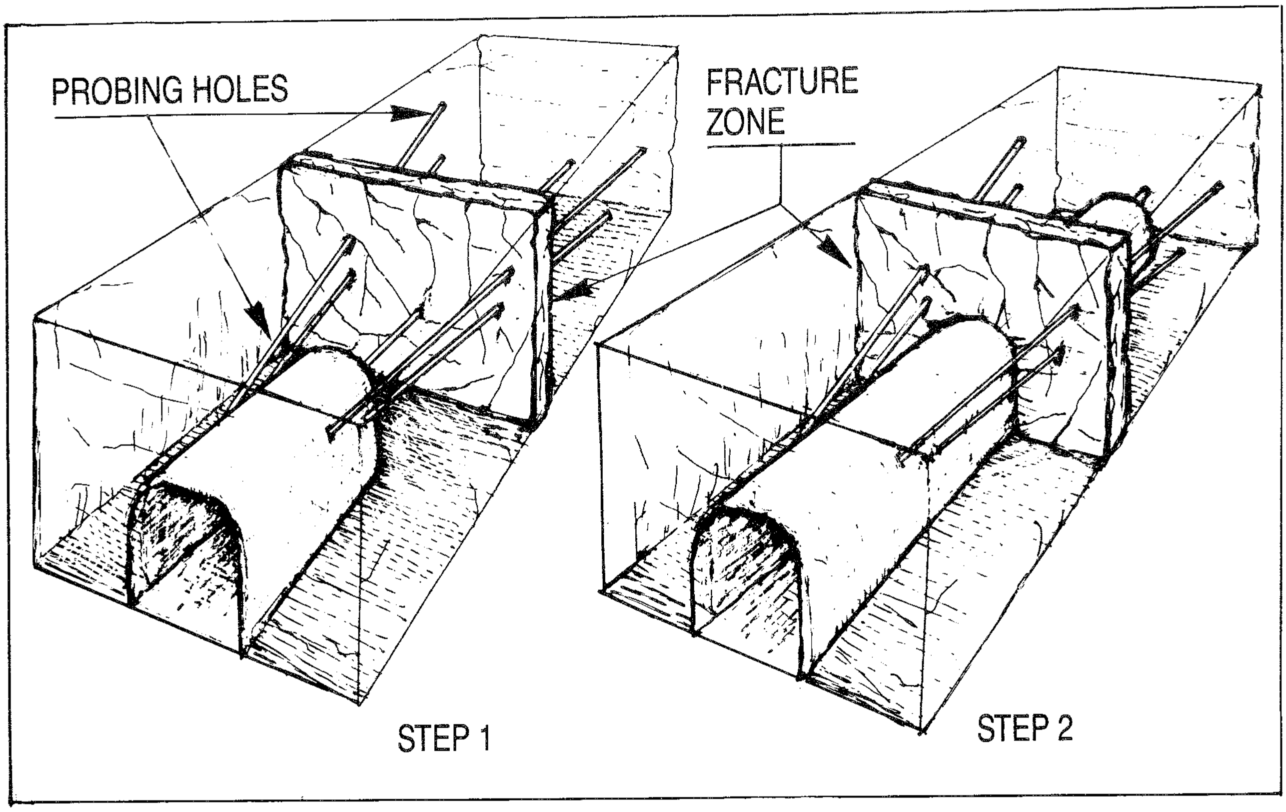


*Figure B-2. Planned probe holes in the side tunnels through an intersecting fracture zone.*

tunnels will be driven out from the access tunnel. A side tunnel will be blasted out if rock requiring extensive sealing and reinforcing work is encountered. The location of the side tunnels cannot be determined now, but in the final expectation model to be presented before the start of the construction phase, approximate locations will be specified for the side tunnels down to a depth of 350 metres. The construction and investigation sequence in the side tunnels is described in brief in the following.

The side tunnels are assumed to have a length of about 40 metres and a cross-sectional area of about 20 $m^2$. As a rule, the tunnels should be driven outside the access tunnel at a gradient of about 2% upward. A measuring weir will be arranged at the opening of the side tunnel and the water from the measuring weir will be diverted to the pipe in the access tunnel.

Like the access tunnel, the side tunnels will be excavated with percussion-drilled probe holes until the distance to the intersecting zone is about 20 metres. At the working face, five holes will be driven through the zone, see Figure B-2. Hydraulic tests will be carried out in the holes. The tunnel will then be driven through the zone. The principle for subhorizontal zones is similar, but then a short raise through the zone will be made.

The investigations in the side tunnels are aimed at characterizing existing conductive zones and providing a basis for characterizing the disturbed zone around the tunnel.

Geohydrological mapping and documentation will be carried out in both the access and side tunnels and leakage to a side tunnel will be recorded at the measuring weir. Furthermore, pressure buildup tests will be carried out in the probe holes. In the five holes that have been percussion-drilled through a zone, pressure buildup tests combined with interference measurements on other boreholes will be carried out, plus a flow test on all boreholes in the group. The data will be evaluated to characterize the zone before the rest of the tunnel is excavated.

After the blasting work is completed, the zone will be documented geohydrologically, the flow will be recorded at the measuring weir and the pressure will be measured in the remaining boreholes to provide a basis for characterizing the disturbed zone around the tunnel.

As with the geological investigations, the above description applies primarily to the investigations down to a level of about 350 m. As before, the results from this first stage will be continuously compiled during execution and may therefore modify the programme during the course of the investigations. For the investigations in Stage 2 (down to the 500-metre level), the general rule is that the degree of detail in the description of the geohydrological conditions in the near field shall increase as the distance to the main level decreases. The investigations in Stage 2 will therefore be increased with a denser documentation (more boreholes) and supplemented with geophysical and hydraulic cross-hole measurements. Since results obtained from the investigations down to the 350-metre level largely determine the plan of the continued geohydrological investigations, it is therefore judged unnecessary to define these more precisely at the present time.

### B 3.4 Predictions

A site-specific geohydrological model of the laboratory and its near field during different stages of construction will be prepared during the preliminary investigation phase in accordance with the "Validation Report" that is currently under preparation. The model will be calibrated against measured groundwater levels, hydraulic tests in and between boreholes and groundwater chemistry. The model will be set up with the geometry for the laboratory that follows from the design documents. For the seepage calculations, it will be assumed that a disturbed zone exists around the access tunnel, which can be given different properties in different calculations. Seepage and drawdown will be predicted for different stages of access tunnel construction.

### B 3.5 Evaluation

The data obtained from the field investigations will be evaluated together with the data from the geological and hydrogeochemical investigations. Of special importance is investigating and evaluating the relevance of the investigations for the geohydrological modelling work.

As the hydraulic properties in the area become known, the above observation series can be related qualitatively and quantitatively to groundwater recharge, groundwater discharge, contact with the sea etc. These are conditions that directly provide indications of boundary conditions for the different models of the area. A running analysis and evaluation activity will therefore be necessary throughout the investigation period.

At the start of construction Stage 2, technology will be available to permit continuous data handling of the interference test involved in the tunnelling. These data will be used especially for characterization of the tunnel's near field.

### B 3.6 Reporting of Results

As with the presentation of the geological investigations, reporting of the results will be coordinated with other subject areas. Compilation of obtained data, evaluation and comparison with expectation models will be performed after the conclusion of the different stages (down to about 350 metres, 500 metres and the excavation of the testing areas). In addition, investigation strategy and investigation methods will be updated, as will the expectation models, before the next stage is begun.

### B 3.7 Construction Works

In addition to the above-mentioned side tunnels and boreholes, measuring weirs will be required every 100–150 metres in the access tunnel and at the mouth of the side tunnels. All work should be carried out by the tunnel contractor.

### B 3.8 Preparatory Work

A draft proposal for the geohydrological work during the construction phase shall be prepared, followed by a detailed programme in July 1990. An organization plan for the field work shall be ready by January 1990, while detailed instructions for the field organization shall be completed by July 1990. This also includes instructions for how the geohydrological observations are to be carried out in connection with injection grouting and extensive reinforcing work.

## B 4 GEOHYDROCHEMICAL INVESTIGATIONS

### B 4.1 Background and Current State of Knowledge

Investigations aimed at clarifying hydrochemical conditions in the bedrock will be carried out during the preliminary investigation phase. This work will be carried out in stages that alternate between measurement, evaluation and prediction, where the collected results are used to predict the conditions and the changes expected during the construction phase. Since the groundwater is mobile, a drainage of shafts and tunnels will bring about a high rate of groundwater flux. Accordingly, the changes that take place in water composition will reflect the hydrogeological conditions.

## B 4.2 Goals

The goal of the hydrochemical investigations during the construction phase is to study changes in water composition and relate these changes to the predictions made during the preliminary investigation phase. The investigations therefore include the following elements:

- Follow changes in the interface between saline and fresh water.
- Study the transport of dissolved substances in a large volume of rock.
- Obtain material for validation of groundwater flow and transport models on a realistic scale.
- Follow changes in the redox conditions in the groundwater.
- Follow changes in the chemical composition of fracture minerals and determine the redox kinetics of the groundwater-fracture-mineral system.
- Develop and test methodologies for detailed hydrochemical investigations on candidate sites.

The investigations are closely linked to the stage goals of the Hard Rock Laboratory: "To verify pre-investigation methods" and "To establish detailed investigation methodology".

The strategy for the methodology used for water sampling, sampling interval and analysis will be evaluated and updated during the course of the work and thereby provide valuable information on how the hydrochemical investigations should be carried out in future site investigations. The hydrochemical changes recorded during the construction phase may prove to be either great or small, and it is only natural that these changes be related to the prevailing geological and hydrogeological conditions. To the extent that such a relationship is simple and the results agree with the expectation model, the method can be used for validation of the preliminary investigation forecast, otherwise only to characterize the groundwater flow in the investigated area. The results of the chemistry validation will be available in good time before the start of the detailed site investigations of the candidate sites.

## B 4.3 Execution

The work will be conducted in parallel with the driving of the access tunnel and the completion of the operating level. It will include studies of changes in the water's chemical composition (natural tracers) as well as non-interacting tracers injected in surrounding boreholes and in boreholes drilled from tunnels as well as through seepage into the facility. The natural tracers should be able to describe the flow paths of the water in the uppermost stratum of the rock, while the injected tracers shall describe the flow paths in the deeper-lying rock.

The fresh water cushion on Äspö will be used to study the flow paths in the near-surface rock (about 100 m). Owing to pressure head drawdowns in the tunnel, fresh water will run down and reach the tunnel in those points where the connection upward is good. In order to study the flow paths in the deep rock, tracers will be injected in conductive zones via the cored holes previously drilled from the surface. Each injection point will have its own tracer and each of an estimated four boreholes will be provided with its own injection level. Injection can take place continuously throughout the construction phase or in impulses at constant time intervals.

Groundwater sampling will take place:

- in percussion boreholes drilled into the rock from the access tunnel (the probe holes described in section B3.4),
- at points where water seeps into the tunnel through the walls and roof,
- in the drainage ditches,
- in fracture zones intersected by the tunnel.

The purpose of the sampling in the boreholes is to clarify changes in the chemical composition of the water. In addition, any drilling water residues from drilling of the deep cored holes and any added tracers will be detected.

Rapid changes are expected in the near-surface rock, so it is important to get the samplings in the access tunnel underway quickly. At the 500 m level, an additional ten or so holes will be drilled for the same purpose. The boreholes to be sampled will be fitted with a packer, hose and pressure transmitter and water samples will be taken via a valve. The sampling frequency will be determined on the basis of the results from the earliest sampled holes.

Water leaking in at distinct points in the tunnel will be collected in funnels. Somewhere on the order of 150 funnels are needed. Small leaks that cannot be collected in funnels will be run down into drainage ditches. The samples will be analyzed for salinity and tracer content.

Fracture zones intersected by the access tunnel are the most probable places to recover tracers. For construction- and safety-related reasons, it will be virtually impossible to investigate and sample these intersecting zones in the access tunnel. However, they can be studied in detail by blasting out side tunnels that pass through the zones at different levels.

Thorough investigations using plastic sheets or the like will be carried out in order to study flow distribution. Due to the large number of seepage points, relatively good statistics can be obtained on the variation in character of the zones. Water samples taken in each separate channel can be analyzed with respect to natural composition and tracer content. The possible influence of injection grouting material can be detected. The flow in the lower part of the side tunnels will be recorded in three shallow cored holes in the tunnel floor and the holes will also be sampled for a complete geohydrochemical characterization. The scope of this characterization is comparable to the borehole investigations carried out from the ground surface. A continuous monitoring of the water composition will then be carried out. This will be of the same scope as the sampling of the percussion-drilled holes in the access tunnel. The same applies to the water collected in the plastic sheets.

Samples taken in fracture zones, in funnels and in boreholes will also be analyzed for tritium in cases where the salinity of the water has decreased since the preceding sampling.

Cores from the holes in the bottom of the side tunnels will be recovered and analyzed at a later stage, providing that oxidizing water is obtained. Mineralogical investigations will be carried out on the fracture minerals to provide a picture of how quickly the oxygen reacts with the redox-sensitive minerals on the fracture faces, ie the kinetics of the redox reactions.

As in the case of the geological and geohydrological investigations, the procedure described above will apply primarily down to the 350-metre level. Experience gained of the investigation methodology and results obtained will then determine the continued programme.

### B 4.4 Predictions

The geohydrochemical predictions will include:

- The chemical composition of the groundwater in surrounding boreholes and of water leaking into the tunnel and changes in this composition as a function of lithology and hydrology.
- Breakthrough (when and where) of injected colour tracers.
- Detection of oxidizing water.

### B 4.5 Evaluation

The evaluation will include a comparison between prediction and obtained results. The expectation models will specify an interval within which obtained data are expected to lie. The final evaluation will result in a model that describes the current and future hydrochemical situation within the area.

### B 4.6 Reporting of Results

Reporting of results will be coordinated with the geological and geohydrological investigations after each stage (at 350 and 500 metres) and after completion of the 500-metre level.

### B 4.7 Construction Works

The percussion-drilled holes in the access tunnel will be drilled by the tunnel contractor under the direction of personnel from the site organization. The equipment and activities in and at the holes do not require any specially excavated niches.

Some analyses of water samples will be done on the site in one of the mobile chemistry labs. The side tunnels must therefore have a free height of at least 3.5 metres and a minimum width of about 5 metres. The investigation of the redox conditions requires three vertical cored holes in the bottom of the side tunnels. The holes shall have a diameter of 76 mm and a depth of 1–2 metres.

### B 4.8 Preparatory Work

A method for detailed sampling of hydraulically conductive fracture zones in tunnels will be developed and tested. Detailed instructions will be prepared and training will take place in the summer of 1990.

## B 5 INSTRUMENTS

### B 5.1 Background

For collection of relevant data for the characterization of geological, geohydrological and hydrochemical conditions that will be carried out during the construction phase of the hard rock laboratory, suitable instruments are required so that this data collection can be carried out efficiently and with high accuracy. During preceding stages of the project, both instruments that have previously been used in connection with site investigations and instruments that have been developed specially for this project have been used.

While the investigations in the preceding stages have been carried out from the ground surface or from boreholes, investigations during the construction phase will primarily be carried out in tunnels and in boreholes drilled from these tunnels. Many of the measuring methods and instruments used for investigations from the ground surface and boreholes can also be used for investigations in tunnels. Data collection in the tunnels will often be carried out under difficult and time-restricted conditions and in connection with or during brief interruptions in the rock construction activities. This imposes special requirements on both personnel and instruments.

The current state of knowledge regarding investigations from underground facilities is based in part on collective experience from Swedish rock construction and in part on more direct experience from the projects which SKB has conducted or participated in, such as CLAB, SFR, Stripa and Hylte.

Large quantities of data will be collected during the construction phase, not only from the tunnel but also from the already existing boreholes. The disturbances caused by tunnel construction in the natural hydrological and hydrochemical conditions must be carefully followed up. The most effective way to do this is by the use of automatic collection systems, specially developed and tested for the purpose.

## B 5.2 Goals

The overall goal for the subject area of instruments is to ensure that suitable instruments for collection of geological, hydrological and hydrochemical data are available and that this data collection can be carried out with the necessary precision and accuracy. In order to achieve this goal, existing instruments can be used in some cases, while in other cases these instruments must be adapted or modified or new instruments developed. For the portion of the data collection performed with stationary installations, large quantities of such equipment must be procured.

The experience gained regarding the function, precision, accuracy, reliability, durability etc of the instruments used is of fundamental importance for establishment of the technology that is required for the detailed site investigations.

## B 5.3 Description of Instrument Needs

### Instruments for Geological Investigations

In connection with the drilling work, the recording of such technical drilling parameters as drilling rate, drilling water pressure etc can make valuable contributions to the interpreting work. This recording can be considerably streamlined by the use of automatic recording equipment mounted on the drilling rig.

The performance of all position measurements in the tunnel with high precision is of crucial importance for both the tunnel itself and for the documentation work in the tunnel. Other aids in mapping and position determination are photo- documentation with a camera, stereo photogrammetry and videofilming. The question of which is the most useful system for the purposes of the project will be examined. For the geological mapping work, aids such as hand-held field computers should be used, with software that permits transfer to CAD.

For geophysical measurements in the short pilot holes, a handy logging outfit should be developed by means of which several selected parameters can be measured at the same time. For optimal utilization of radar methods, antennas that are specially intended for measurements in tunnels will be developed. Radar should then be able to be used both for forecasts of sections in front of the tunnel face and for documentation. These measurements will be carried out either as tunnel measurements, borehole measurements or combined tunnel/borehole measurements.

### Instruments for Geohydrological Investigations

Data collection for the geohydrological documentation mainly includes measurement of flow and pressure head. The predominant source of disturbance of the hydrological conditions is the tunnel construction work itself. Beyond this disturbance, minor disturbances are created when boreholes are drilled and flow tests are conducted in them. These disturbances cause a pressure head reduction in the surrounding rock volume, and the extent of this pressure head reduction reflects the geohydrological conditions in the rock and must be measured. This is done by recording the pressure head in a large of boreholes, both those that have been drilled in earlier stages from the ground surface and those that have been drilled in the tunnel. This pressure recording requires the installation of one or more packers in the boreholes and automatic data collection by means of pressure transmitters and data loggers. The measuring system must be so designed that it is able to withstand conditions during ongoing blasting work while fulfilling the necessary requirements on precision. Accuracy of measurement must be checked continuously by means of a built-in calibration system, probably through a reference pressure line. Each data logger will be in data communication with a mainframe computer on the ground surface for centralized data processing. For measurement of flows, measuring weirs will be established in sections along the tunnel for recording of water seeping into the tunnel. Specific flow points will be measured separately, and moisture transport through the ventilation air should also be measured. Suitable systems for this type of data collection will be developed, along with flowmeters for recording of flow from boreholes.

### Instruments for Geohydrochemical Investigations

For hydrochemical investigations, equipment is required for sampling of water and analysis of water samples. In most contexts, sampling of water does not require any special equipment as far as boreholes in tunnels are concerned. For existing boreholes from the ground surface equipped with packer equipment and pressure recording systems, however, a special sampler must be developed. The same also applies to boreholes in "impervious" rock in the tunnel, where sampling and analysis of "stagnant water" is planned. One of SKB's existing field laboratories will mainly be used for analysis of water samples. Special samples will be sent to other analytical laboratories.

Artificial tracers for tracer tests will be injected in those sections of the boreholes drilled from the ground surface that have previously been prepared with equipment for this purpose.

# C PRELIMINARY PROGRAMME FOR INVESTIGATIONS AND TESTS DURING THE OPERATING PHASE

## C 1 GENERAL

It is assumed that the investigations during the operating phase will be carried out for the most part at a depth of 500 metres. As additional data is obtained from the investigations during the construction phase, the expectation models for the 500-metre level will be updated and the preliminary design of tunnels for the proposed experiments will be revised. The final design will be based on a detailed characterization of the bedrock during the latter part of the construction phase. Each test at the 500-metre level will be preceded by a thorough characterization of the bedrock around the drift or drifts where the tests will be carried out. The purpose of these pre-investigations is to validate expectation models set up previously and to determine the boundary conditions that apply for the tests and that will be required later for evaluation.

The design of the tests and experiments during the operating phase described below shall be regarded as preliminary and will be revised as experience is gained during the period up to execution.

The programme for the operating phase will gradually be supplemented, depending on such factors as the final choice of repository system. If subsequent considerations should lead to the selection of a considerably greater final repository depth than 500 m, the programme will be further supplemented.

## C 2 LARGE-SCALE TRACER TESTS

### C 2.1 Background and Current State of Knowledge

The predominant groundwater flow in the bedrock takes place in a very limited portion consisting of fractures and fracture zones. Previous studies have shown that the character and properties of these fractures and fracture zones often vary between different geographic areas, between different rock types and sometimes even within the same rock type on the same site. It is therefore important to carry out tracer tests on different scales and on different sites in order to find out more about groundwater flows and flow paths in a fractured rock mass. Besides being in itself a method for describing geohydrological conditions in the bedrock, the execution of tracer tests is one way to validate expectation models of these geohydrological conditions, especially transport of solutes in the rock.

Tracer tests for the purpose of studying the transport of solutes in the rock have been carried out at Studsvik, Finnsjön and Stripa. Knowledge in this field has thereby increased considerably and has lately led to a more detailed picture of the groundwater flow in the rock. This is particularly true of the distribution of the water flow in fractures and the flow pattern in these fractures. Different calculation models for describing this are currently being tested.

Tracer tests in individual fractures have been carried out and are being carried out at Stripa. Large volumes of low-conductivity rock of repository quality have also been investigated by means of tracer tests. In the so-called 3D test at Stripa, a tunnel was used as a catchment area to study the distribution of water flow and transport pathways, while tracers were forced out into very low-conductivity parts of the rock in diffusivity tests to ascertain the diffusion properties of undisturbed rock.

Tracer tests in fracture zones of considerably higher conductivity than the surrounding rock have been carried out at Studsvik and Finnsjön. Injection and sampling of tracers has been performed via boreholes from the ground surface.

The hydraulic investigations, tracer tests and even radar surveys that have been carried out indicate that the pattern of flow distribution in low-conductivity rock, and the chances of characterizing this, are site-specific. This is even more true of fracture zones, which have proved to have different conductive properties on different sites, despite similar geometric conditions.

In order to study the site-specific flow paths existing in the bedrock around the hard rock laboratory, tracer tests on different scales will be performed. As described in Appendices A and B, large-scale tracer tests will begin in the steady-state phase before the start of construction and will continue throughout the transient construction phase. The results obtained from these tests will constitute a basis for the planning of tracer tests during the operating phase.

### C 2.2 Goals

The goals of the large-scale tracer tests during the operating phase are to:

- Study the transport of solutes in a large volume of the rock.
- Provide a basis for validation of models for groundwater flow and transport on a realistic scale.

The work is of great importance for the main goals of the hard rock laboratory: “To test the quality and usefulness of methods for rock characterization” and “To collect material and data for safety assessment”.

The large-scale tracer tests are mainly of importance for the stage goal "To test models for groundwater flow and transport of solutes". Together with the tracer tests performed during the construction phase, with the blockscale tracer tests, with hydraulic tests and interference tests, and with similar investigations on other sites (Stripa, Finnsjön), the obtained data will provide a broad database on groundwater flows and flow paths on different scales and under different conditions. This database will be used to test, calibrate and, wherever possible, validate models for groundwater flow in fractured rock. The models shall above all be used in the assessment of the long-term of the safety of the final repository that will be submitted together with the siting application. They should also be able to be used for optimization of the final repository. The database will be able to be further supplemented with data from detailed investigations on the proposed final repository site(s).

## C 2.3 Execution

The large-scale tracer tests during the operating phase are a direct continuation of the studies during the construction phase, and their execution will therefore be based on the results obtained from this previous phase. The investigations are preliminarily divided into the following stages:

| | |
|---|---|
| Stage 1: | Planning and predictive modelling of the tests. |
| Stage 2: | Preparations – Instrumentation of injection boreholes and sampling boreholes. |
| Stage 3: | Execution – Injection of tracers and sampling, analysis and data processing. Data will be collected and stored in the same type of database as for the block-scale tracer test. |
| Stage 4: | Evaluation and validation |

## C 2.4 Predictions

As mentioned previously, the results of the geohydrological and groundwater chemistry investigations during the construction phase form a basis for the prediction of the large-scale tracer tests. The prediction should therefore be able to be made in great detail. Among other things, breakthrough curves, transport pathways and recovery should be able to be predicted. The degree of uncertainty in the predicted quantities will be specified. If possible, several different groups of researchers will be given an opportunity to participate in the predictive modelling.

## C 2.5 Evaluation

Evaluation will be carried out in the form of a comparison between prediction and obtained results, where the prediction indicates the expected level.

## C 2.6 Reporting of Results

Reporting of results will take place in connection with the different stages. Measurement data will be stored in a database of the same type as for the block-scale tracer test.

## C 2.7 Preparatory Work

Preparatory R&D work is needed to obtain a catalogue of usable tracers and their properties. At present, investigations are being conducted for the purpose of clarifying which tracers might be used. This work is being done within the Hylte and Finnsjö projects and is directly applicable to tracer tests in the Hard Rock Laboratory. A summary of results from Hylte and Finnsjön, combined with experience from Stripa, can be included in a tracer catalogue. This catalogue should be available as soon as possible so that the tracer test during the construction phase can be conducted with proven tracers.

Special instrumentation will be required for injection of tracers. This instrumentation could be a modification of the equipment used in earlier tests.

# C 3 BLOCK-SCALE TRACER TESTS

## C 3.1 Background and Current State of Knowledge

The predominant groundwater flow in the bedrock takes place in a very limited portion consisting of fractures and fracture zones. Previous studies have shown that the character and properties of these fractures and fracture zones often vary between different geographic areas, between different rock types and sometimes even within the same rock type on the same site. It is therefore important to carry out tracer tests to different scales and on different sites in order to find out more about groundwater flows and flow paths in a fractured rock mass. Besides being in itself a method for describing geohydrological conditions in the bedrock, the execution of tracer tests is one way to validate expectation models of these geohydrological conditions, especially transport of solutes in the rock.

## C 3.2 Goals

The situation in a final repository with canisters deposited in rock of low hydraulic conductivity and with a "respect distance" to the nearest major water-bearing zone will be simulated in the study. The results of the study will be evaluated and used to validate transport models on a block scale, ie over distances of 10–100 m.

The study will also indicate our ability to characterize and select volumes of sound rock for deposition. Transport models will be used to test the possibility of predicting the migration of dissolved substances in a selected volume of low-conductivity rock adjacent to a fracture zone.

The goals of the study can therefore be summarized as follows:

- study the transport of dissolved substances in the rock over distances of 10 – 100 m,
- validate models for transport in sound rock to a fracture zone,
- validate models for transport in a fracture zone.

The study is of great importance for the three main goals of the hard rock laboratory.

The block-scale tracer tests are mainly of great importance for the stage goal "To test models for groundwater flow and transport of solutes". This modelling is of central importance for the assessment of the long-term safety of the final repository that will be submitted together with the siting application.

## C 3.3 Execution

As a basis for the geological and geohydrological characterization of the 500-metre level, a block (about 50 x 50 m) will be selected that contains both sound rock and a conductive zone. This will simulate the conditions in a final repository where high-level waste is deposited in rock of low hydraulic conductivity but with a respect distance to a large water-bearing zone.

Injection of tracers will be done both in the sound rock and in the fracture zone, while sampling will be done only in the fracture zone. In this way, transport both along the composite flow paths and in the zone itself can be studied. By injecting different tracers in different sections and detecting them in a tunnel that intersects the zone, information can be obtained on flow paths. The pattern of outflow in the tunnel walls and the breakthrough curves will be predicted, as far as possible, on the basis of an initial characterization of rock and fracture zone. Any fast channels will be identified and described.

A schematic drawing of the experiment is shown in Figure C-1.

The preliminary siting in the Hard Rock Laboratory of the test will be included in the expectation models prepared during the construction phase. The geological and geohydrological investigations on the experiment level will provide information on the final siting and design of the tests.

The tests will be carried out in stages to permit predictions between each stage and modifications of the procedure.

| | |
|---|---|
| Stage 1 | A tunnel will be excavated through a conductive zone and mapped in terms of geology and hydrogeology. The different inflow points in the tunnel will be separated and measured by covering the tunnel with plastic as in the 3D tests at Stripa or by means of a similar arrangement. |
| Stage 2 | A few tens of metres from the tunnel that intersects the zone, see Figure C-1, an injection borehole will be drilled through the zone and another ten or so metres further. Hydromeasurements will be performed in the borehole and between the injection hole, the tunnel and selected sampling points. Dilution measurements will be carried out in different parts of the injection hole. |
| Stage 3 | The injection borehole will be sealed with packers and tracers will be injected mainly into the sound rock and also into the zone. The breakthroughs will be followed in the tunnel and in the sampling holes.<br>Rock samples from the fracture zone and from the low-conductivity rock will be sent to a laboratory for characterization of fracture geometries, diffusion properties and fracture minerals.<br>The results from the characterization of the rock volume and the zone will be reported and stored in a database so that users of different models can carry out predictive modelling. |

## C 3.4 Predictions

The predictions will be linked to the different investigation stages. A more extensive predictive modelling will be carried out prior to the second stage. Various possible models should be tested to describe how the tracers will migrate. If possible, several modellers will be given an opportunity to process data. The database shall include: breakthrough curves, distribution of transport pathways and recovery of tracer. Model calculations will be carried out as a part of the test planning. The intention is to start with non-interacting tracers and finish with weakly sorbing substances.

## C 3.5 Evaluation

The results will be compared with the previously made predictions. If possible, the comparison will be used to discriminate between the different models. It is essential that the laboratory results be weighed into the final model. Data from migration experiments will be included for the weakly sorbing tracers.

## C 3.6 Reporting of Results

Reporting of the results of both the individual experiments and the predictive modelling will be done stage by stage. Written reports and storage of data should be finished before the next stage is begun.

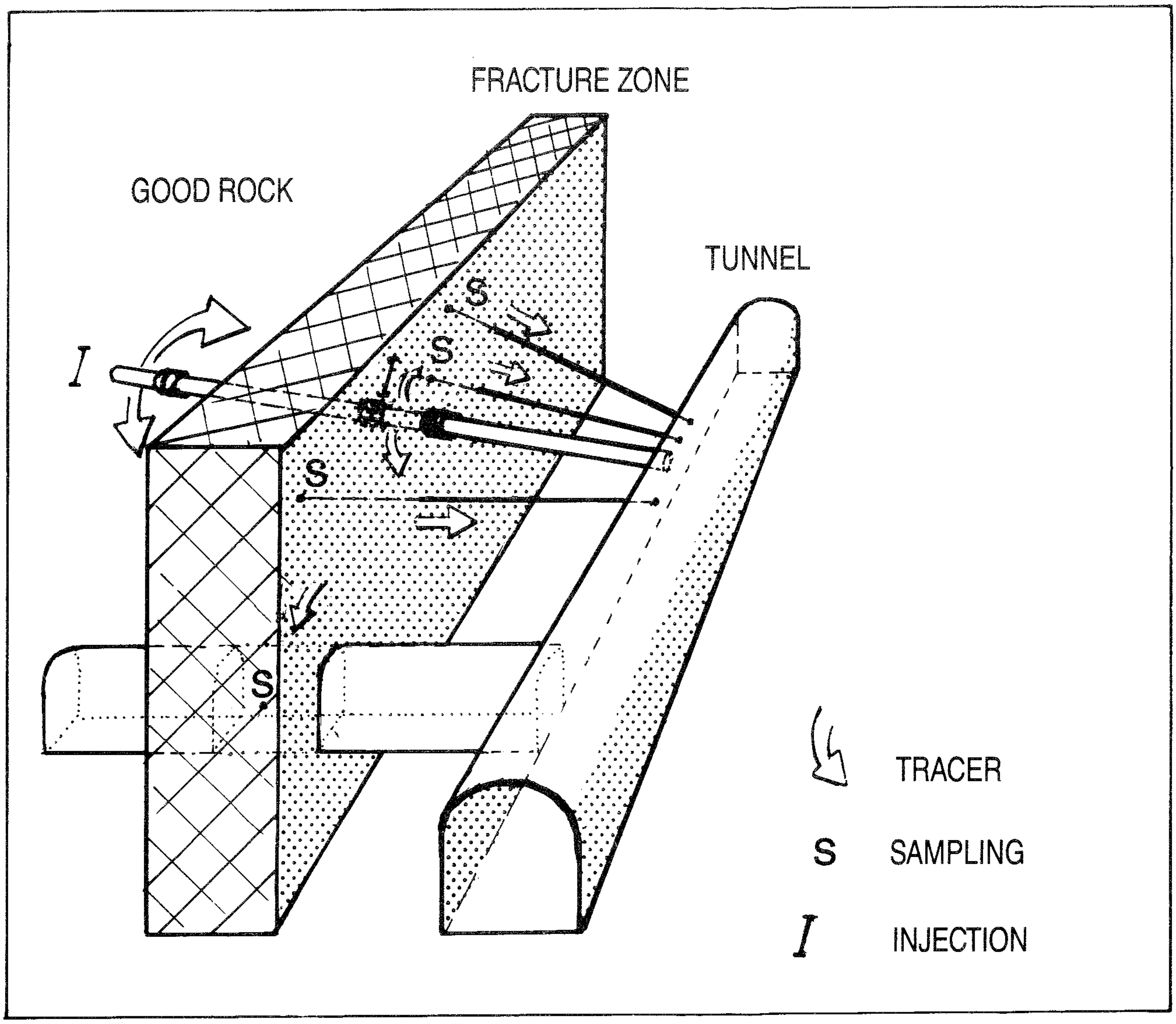


*Figure C-1. Block-scale tracer test – schematic diagram.*

## C 3.7 Construction Works

The tests should be kept in mind during the construction phase and possible sites should be proposed early on. The test site must be selected so that disturbances from the facility do not influence the tests. Boreholes must be drilled and an entrance tunnel driven into the zone. No special buildings are required. The tunnel should be at least 20 m long. The feasibility of full-facing boring of the tunnel should be explored. If the rock block is located adjacent to the access tunnel, a niche will be blasted out.

# C 4 RADIONUCLIDE MIGRATION

## C 4.1 Background and Current State of Knowledge

Previous investigations have shown that solubility, sorption on fracture faces and diffusion into the rock matrix prevent or reduce the dispersal of radionuclides in the bedrock. But the data and the models that describe the chemical properties of the radionuclides in the natural bedrock environment are based primarily on laboratory tests. The following test conditions are very difficult to simulate in the laboratory, however:

- natural reducing conditions,
- natural content of colloidal particles,
- undisturbed rock, ie rock with micropore systems and even large fractures that have not been depressurized through sampling.

All of these conditions are of extremely great importance for the rock as a barrier, since they have a great influence on the solubility or retention of radionuclides.

Experience gained from Stripa and SFR also show that it is important to have a section in a underground facility with constant access to groundwater, fractures and fracture zones for migration experiments, geochemical sampling and material testing for a period of least five years, or as long as the facility is kept open.

## C 4.2 Goals

The goals of the investigations are:

- Test the dissolution and migration of radionuclides in situ.
- Test the influence of natural reducing conditions on the solubility and sorption of radionuclides.
- Test the ability of the groundwater to absorb and transport radionuclides and natural colloids and microbes, humic substances and fulvic acids.
- Validate models and check constants that are used to describe radionuclide dissolution in groundwater, sorption on mineral surfaces, diffusion in the rock matrix, transport in an individual rock fracture and radiolysis.

The goals are of great importance for the third main goal of the activities in the hard rock laboratory, namely to "Collect material and data for the safety assessment". The tests are of very great importance as a basis for the analysis of the transport of solutes in the groundwater and thereby for the assessment of the long-term safety of the repository. An account of this will be submitted together with the siting application.

## C 4.3 Execution

Part of the 500-metre level will be reserved for the execution of the study, which should be able to continue for a long time. A gallery approximately 40 metres in length will be driven into the rock up to a few tens of metres from a water-bearing zone that can supply deep undisturbed groundwater for a long period of time, see Figure C-2. For this reason, a location far down in the Hard Rock Laboratory should be chosen. The experiment area should be large enough to hold a chemistry laboratory. A mobile chemistry unit can be used, but it should be somewhat differently equipped than for water sampling alone. It shall be possible to characterize the redox properties of the water, which means that redox analysis equipment must be provided, although an ion chromatograph, for example, is not necessary. On the other hand, the laboratory must have equipment for the handling and analysis of radionuclides.

A FORALAB probe or similar equipment will be used for tests inside the water-bearing zone. No water that passes the probe goes back to the rock, which means that at least short-lived radionuclides can be used in the probe. It shall also be possible to install a radiation source in the probe. Groundwater will also be conducted from the zone into the underground chemistry laboratory for further experiments. The following experiments are planned in the probe, the laboratory section and the fracture zone.

### Experiments in the Probe

Solubility of actinides and technetium under natural reducing conditions, dissolution of simulated fuel and influence of radiolysis on fuel dissolution and the near field.

Sorption of actinides and technicium under natural reducing conditions. Both batch and column tests as well as migration in rock fractures will be carried out inside the probe. The rock fractures are contained in drilling cores, ie overcored fractures that have then been installed in the probe.

### Experiments in the Chemistry Laboratory

In part a repetition of the tests in the probe for purposes of cross-checking. Analysis of colloids, microbes, humic and fulvic acides. Test of the ability of this equipment to absorb and transport radionuclides with hollow-fibre filtering, eluation of ion exchange resins or other suitable techniques.

### Experiments Out in the Fracture Zone

An injection hole will be drilled into the fracture zone a few metres from the sampling point used for the probe. Migration tests with sorbing radionuclides and coprecipitation tests with uranium and actinide analogs will be carried out in the transport pathway from the injection point to the sampling point. Tests of colloid formation and transport with precipitated colloids will also be conducted.

The same area, laboratory equipment and sampling/injection points in fracture zones will be used for the redox tests described in Section C-5 "Block-scale redox tests".

### Experiments in the Rock

The following tests will be carried out to the extent that they have not been completed at Stripa in the meantime.

In-diffusion of sorbing nuclides in the micropores in the rock will be tested by injecting sorbing inactive isotopes, for example inactive cesium and strontium, together with non-sorbing tracers in undisturbed parts of the rock. The injection and sampling procedure has already been developed at Stripa.

A water-bearing fracture will be selected for tests for sorbing radionuclide-like substances. Two holes will be drilled parallel and along the fracture, spaced at a metre or so. Sorbing substances will be injected and the utilized sorption faces in the fracture, as well as penetration into the rock, will be determined after excavation of the fracture (overcoring).

### Miscellaneous

The same area and chemistry laboratory can also be utilized for long-term tests of material and material combinations. The technique for such material tests has been developed at Stripa. Examples of materials

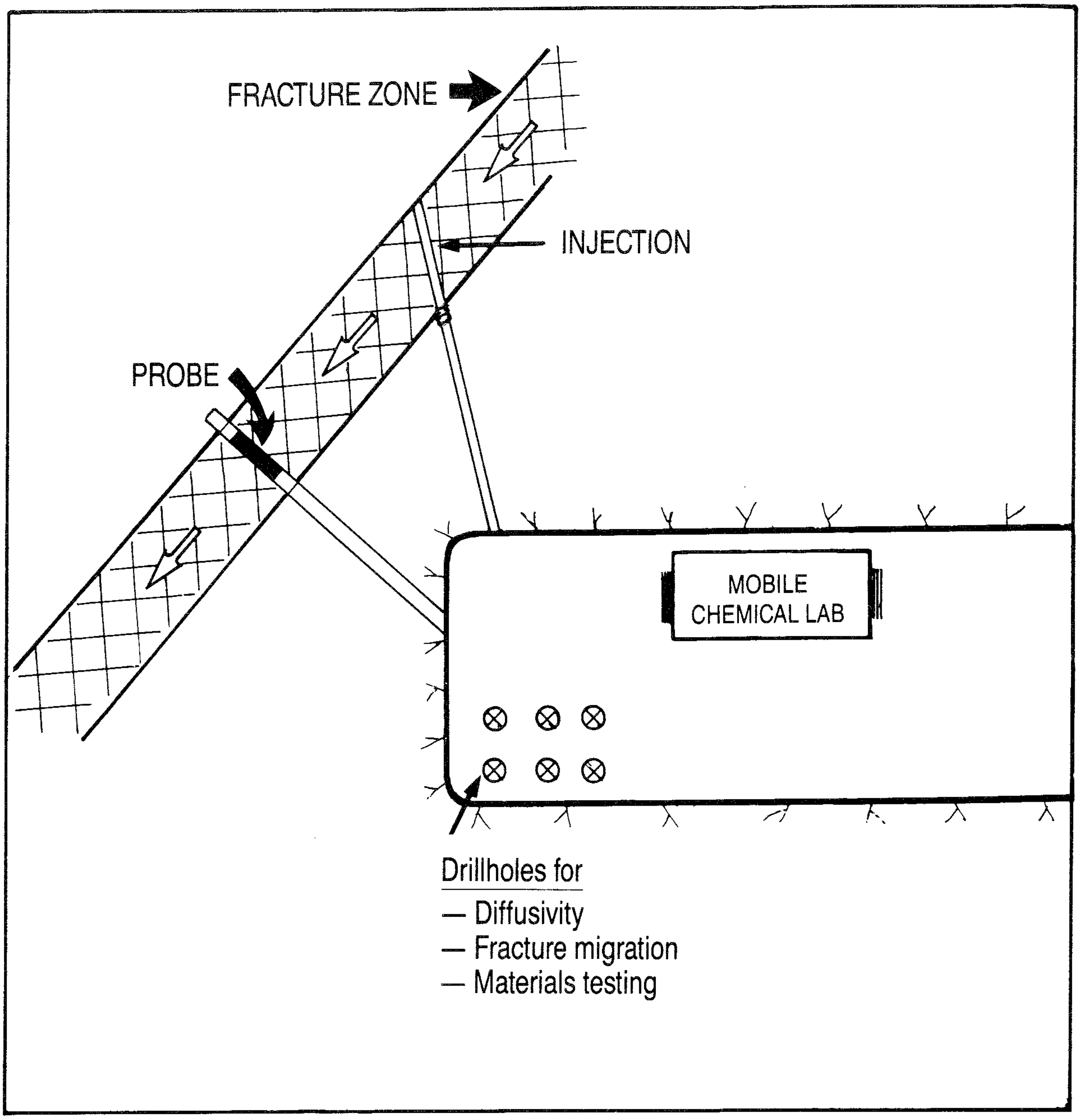


*Figure C-2. Radionuclide migration – schematic diagram.*

and material combinations of interest are: copper, iron, bentonite, concrete, uranium dioxide, concrete-bentonite, iron-bentonite, uranium dioxide-bentonite. The goal of the material testing in situ is to validate models for corrosion and other changes as well as the interaction between different materials.

To facilitate planning and execution, the work will be done in stages. Those experiments that disturb the natural environment have been scheduled for the later stages.

Stage 1 The chemistry laboratory will be installed. The groundwater from the zone will be conducted to the chemistry laboratory for characterization and experiments.

Stage 2 The probe will be installed in the borehole and experiments will be conducted in the probe. Water will be conducted to the chemistry laboratory for monitoring of the probe, cross-checking of the tests and parallel experiments.

The probe will have to be taken out and re-rigged for the different tests that are to be performed in it. It may prove necessary to use different types of probes.

Stage 3 Another hole will be drilled in such a manner that it intersects the zone a few metres from the first sampling point. The connection will be characterized by hydraulic measurements and possibly radar.

Stage 4 Migration tests will be carried out over the few metres that separate the boreholes in the zone. Sorbing nuclides or nuclide-like substances will be used. Co-precipitation tests will be performed with uranium and actinide analogs. Transport with colloids and organic complexes will be tested.

The experiments described under the heading "Experiments in the rock" and "Miscellaneous" will be carried out when necessary in parallel with or after the above stages.

## C 4.4 Predictions

The results obtained from the studies will be reported after each stage together with a description of the activities in the subsequent stage. A predictive modelling of the migration tests with sorbing tracers, the co-precipitation tests and the experiments with colloid transport will be carried out prior to Stage 4. Transport models that include chemical conditions and are based on laboratory tests will be used for this purpose.

## C 4.5 Evaluation

The tests shall show that the expected chemical reactions take place in situ and with the capacity and yield predicted by laboratory tests and calculations. The uncertainties in data describing solubility, sorption and diffusion are often an order of magnitude and expectations on agreement between tests and calculations must naturally be adjusted to this. It is essential to actually verify the occurrence of reactions of importance for safety as well as to be able to specify a minimum limit for the capacity of the natural rock-groundwater chemical system that is available to reduce, pH-buffer and sorb radionuclides and radiolysis products.

## C 4.6 Reporting of Results

Written reports shall be submitted before the next stage is begun. Since tests of slightly different kinds can be conducted at the same time, the reports shall be introduced with a summary. The accounts of the individual experiments shall be attached as appendices.

In order that other groups with other model assumptions shall be able to participate in the prediction and evaluation of the migration tests, the results of hydraulic measurements and data from tracer tests shall be stored in a database. Hydrochemical data shall be stored in SKB's geodatabase GEOTAB.

## C 4.7 Construction Works

The choice of site for the test shall be based on the characterization of the 500-metre level where the existence and character of the fracture zone have been verified and studied in the geohydrological studies of the area. The preliminary siting of the test will be included in the detailed expectation model of the 500-metre level set up before the level is excavated.

The site must be chosen so that undisturbed deep groundwater can be obtained from the selected zone over an extended period of time. A location far down in the Hard Rock Laboratory is preferable.

A gallery about 40 metres in length shall be excavated. A hole shall then be drilled into the zone.

A mobile chemistry laboratory, equipped to handle radionuclides as well, will be placed in the gallery. No special buildings are required.

In a later phase, Stage 3, at least one additional hole will have to be drilled into the zone.

## C 4.8 Preparatory Work

Equipment and suitable radionuclides or radionuclide-like substances must be developed.

The experiments in the probe and out in the fracture zone need to be prepared by laboratory tests. To some extent this can be arranged by a reordering of priorities in ongoing research programmes with a focus on those tests that will later be carried out in the hard rock laboratory.

In Simpevarp there is a laboratory in CLAB that has facilities for working with radionuclides. Preparations can be made for carrying out some of the supplementary aboveground experiments there by locating some of the initial activities there as well. Resources will have to be allocated for this.

The radionuclide chemistry experiments that have been proposed to be carried out in the probe and out in the fracture zone have scarcely been tried at all in situ before. To facilitate detailed planning of the tests, development of equipment and radionuclide or radionuclidelike substances, it would be desirable to carry out simple preparatory studies in situ before the chemistry laboratory section has been built and fitted out. The preliminary tests would consist of both equipment tests and pilot experiments concerning the redox reactions, sorption and colloid transport of radionuclides.

Data and models for describing this type of test are available to a large extent. The exception is models for colloid transport and models that link chemical reactions with transport. The latter are currently under development.

## C 5 BLOCK-SCALE REDOX TESTS

### C 5.1 Background and Current State of Knowledge

Reducing conditions at repository depth are a necessary requirement for long life of a waste canister. The groundwater that has been sampled on different occasions and on different sites within the study-site investigations is always reducing, which proves the reducing properties of the rock. The kinetics of the redox reactions between the minerals in the bedrock and the groundwater require further elucidation, however. Opportunities will exist to study these reactions during the construction phase, when oxidizing water will enter the facility. The study of the effect of the oxygenated water will be performed on a "block scale" (several tens of metres), permitting all relevant parameters to be checked and providing an opportunity for an assessment of the rate of the exchange reactions.

### C 5.2 Goals

The goal of the study is to determine the reaction kinetics when oxidizing water is transformed into reducing water by correlating flow rate with mineralogical changes.

The study is closely linked to the main goal of the hard rock laboratory: "To collect material and data for safety assessment".

### C 5.3 Execution

The test will be carried out in connection with the study concerning "Radionuclide migration", see section C.4. The same well-characterized fracture zone will be used to study how a redox front migrates. Hexavalent uranium and oxygenated water will be injected in a borehole, see Figure C-2. The migration of the redox front and co-precipitation reactions and colloid formations will be studied by overcoring sections of the zone.

Progressively stronger oxidants will be injected during the course of the experiment. Uranium(VI)carbonate will be injected to start with. The purpose of this experiment is to study the kinetics involved when the uranium is reduced to quadravalent and thereby precipitates on the fracture faces. The experiment will continue until the concentration of uranium in the water is the same in the pump hole (the probe hole in Figure C-2) as in the injection hole. During the course of the experiment, samples will be analyzed with respect to the tracers that are expected to precipitate together with the uranium and the substances that otherwise participate in the redox reactions.

In conclusion, oxygenated water will be injected to compare the redox kinetics of the oxygen reduction with those of the uranium reduction. In this way, the results of the investigations during the construction phase regarding redox conditions can be related to uranium reduction in the flow paths.

In order to enable local variations to be taken into account, the experiment will have to be performed at least two different locations.

### C 5.4 Predictions

The purpose of the test is to provide data that can be used in the form of calculation constants. The planning of the test in itself entails certain expectations as to the results. Thus, the sizing of the test will in itself constitute a prediction based on the estimated redox capacity of the zones and expected reduction rates.

### C 5.5 Evaluation

The test will be evaluated in chemical terms. The reaction rate for the reactions that have been identified will be determined. The test may be considered to fulfil its goals if the redox kinetics for the different reactions can be determined.

### C 5.6 Reporting of Results

Result reports will be compiled for each individual study.

### C 5.7 Construction Works

The test will be conducted at the same location as the "Radionuclide migration" study and requires no additional civil engineering works.

### C 5.8 Preparatory Work

In connection with the planning of the test, laboratory tests similar to the field test will be required. Parts of the preparatory work coincide with the preparations for the "Radionuclide migration" study. The investigations that must be carried out in the laboratory are described below.

**Reduction of oxygen in contact with mineral.** These investigations are required in order to be able to size the field test. Flow rate and mineral surface area are of the greatest importance. Different kinds of rock must be studied. The investigations should be based on experience from previous tests, some of which have been conducted at the Department of Organic Chemistry at the Royal Institute of Technology in Stockholm.

**Reduction of hexavalent uranium in contact with minerals.** The purpose of the tests is the same as for the reduction of oxygen.

**The redox buffer capacity of the rock.** This determines how many injections can be made in the zone. It is therefore necessary to know the capacity of the rock as a function of the contact time. At the present time, we only know that the immediately accessible capacity is limited.

## C 6 METHODOLOGY FOR REPOSITORY CONSTRUCTION

### C 6.1 Background and Current State of Knowledge

In connection with the construction of a final repository, it is necessary to carry out a number of investigations for the purpose of determining whether the rock formation possesses the quality that is required for the natural barrier around the repository. The investigations can be divided into the following steps:

| | |
|---|---|
| Step 1 | Investigations on the ground surface and in holes drilled from the ground surface. |
| Step 2 | Investigations on the rock face along the access to the repository (shaft or tunnel) and in holes drilled from this access. |
| Step 3 | Investigations on the rock face and in boreholes at the repository level. |

Steps 1 and 2 are primarily intended to find a site for the repository with homogeneous rock of low hydraulic conductivity. Step 3 is largely aimed at characterizing the rock in the immediate vicinity of the repository.

The execution of the investigations is dependent on the choice of system for the final repository. The following description explains how a test can be carried out based on the geometry of the KBS-3 method.

The expressions "far field", "near field" and the "immediate near field" are often used in discussions of the safety aspects of a final repository. However, there are conflicting definitions of the limits of these areas. Figure C-3 shows the general limits of these different fields.

Characterization of the far field will take place primarily in Step 1, ie through studies on the ground surface and in holes drilled from the ground surface. Supplementary studies will be performed along the access to the repository in Step 2. These investigations are not included in the present proposal for investigations during the operating phase of the Hard Rock Laboratory.

KBS-3 defines the near field as "the area around the canister where the repository and its components directly affect the dispersal of nuclides that occurs when the canister has been penetrated. The effect can be of a chemical, hydrological or mechanical nature. The extent of the near field varies in time and cannot be specified exactly, but can in practice be considered to extend up to a dozen or so metres from the canister". In the following research proposal, the near field thus also includes the rock volume between the deposition tunnels (approximately 30 metres in a single-level repository according to KBS-3).

The expression "the immediate near field" is limited to the bedrock in the immediate vicinity of the deposition holes. It also includes buffer material that penetrates into existing fractures.

Extensive experience has been obtained from previous SKB studies regarding instruments and methods for characterization of the near field. This experience especially consists of results from the joint research in the Stripa project (radar, seismics and hydraulic measurements etc). Experience from the proven investigation methods within the study sites has also improved our ability to characterize the near field. Furthermore, tunnelling work in Sweden and abroad has taught us how to predict intersecting water-bearing fracture zones and how to seal them to prevent water seepage into the tunnel.

Notwithstanding this experience, there has as yet been no complete demonstration of how to characterize the near field in a final repository.

### C 6.2 Goals

The goal of the investigation is to demonstrate on a natural scale how characterization of the near field can be carried out in a final repository. The investigation can be divided into the following sub-goals:

- Develop a strategy for characterization of the near field.
- Demonstrate in an approviately selected rock volume how characterization is to be carried out.
- Show how flexibility can be achieved, ie adaptation of deposition tunnels and deposition holes to the properties of the rock.

Another purpose of the investigation is to characterize the rock volume where the investigation described in Section C 7 "Pilot tests, repository systems" will be carried out. The influence of the buffer material on the "near field" and the "immediate near field" will be investigated and demonstrated in this test.

For natural reasons, the investigation is closely linked to all of the main goals of the hard rock laboratory as well as to the stage goal "To demonstrate construction and handling methods".

It should be pointed out that construction of the repository may require the development of tunnelling methods, methods for excavation of canister pits, injection grouting and repository sealing. These needs have been identified, but planning has not yet begun, see further section C 7.

### C 6.3 Execution

Demonstration of the characterization of the near field in a final repository is limited in the following to the deposition tunnels and the deposition holes. The work will therefore start from a simulated central tunnel

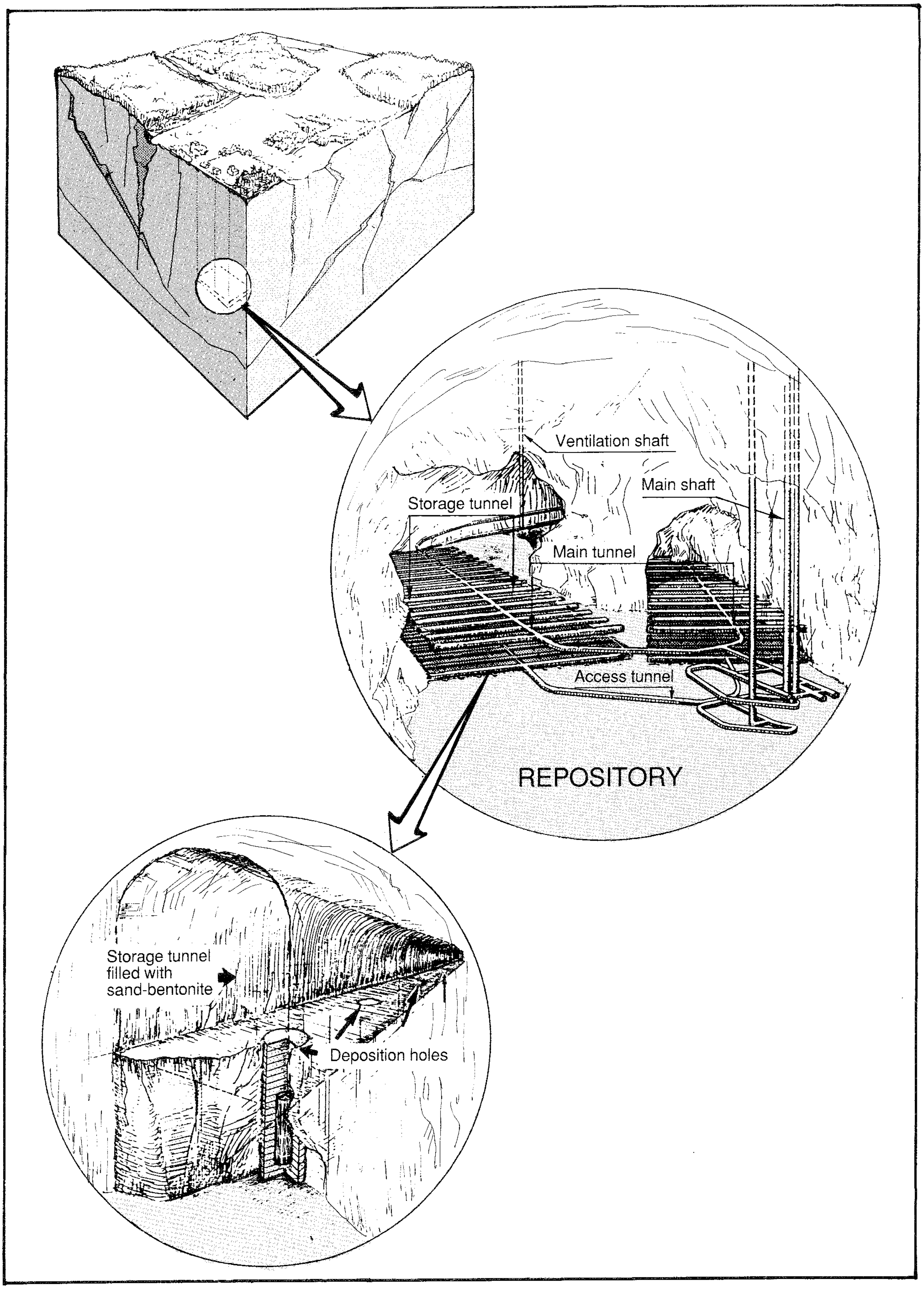


*Figure C-3. A schematic picture of the "far-field", "near-field" and the "immediate near field" to the deposition holes.*

about 300–500 metres in length. This tunnel can be conceived of as comprising a main tunnel in the Hard Rock Laboratory, from which galleries radiate for the different experiments during the operating phase.

An overall description of the investigation is provided below. A more detailed study of the possible geohydrological characterization of the near field around a final repository is already being conducted within the framework of SKB's other R&D work.

### The deposition tunnels

The strategy for characterizing the near field around the deposition tunnels is based on:

- Information from previous investigations and expectation models.
- Information from pilot boreholes and measurements performed in them.
- Information from measurements performed during the blasting of the deposition tunnels.
- Information from mapping and recordings after blasting of the tunnels.

Four deposition tunnels, with a maximum length of 100 metres, are planned to be excavated at intervals of at least 30 metres. Four pilot holes, with a maximum length of 125 metres, will be core-drilled, spaced about 100 metres apart in the planned direction of the deposition tunnels, outward from the main tunnel. (The length of pilot boreholes and deposition tunnels is in part dependent on the subsequent investigation concerning "Interaction between rock and buffer material" in these tunnels.) The location of the pilot boreholes is determined on the basis of the results of the mapping of the main tunnel and the subsequently updated expectation model of the properties of the bedrock. Mapping of cores, rock stress measurements, water analyses, geophysical and hydraulic measurements will provide a basis for further updating of the expectation model.

The pilot boreholes will be equipped with multi-packer systems positioned so that the identified water-bearing zones can be correlated in connection with created pressure changes. It is important here that no other activity in the Hard Rock Laboratory should disturb the controlled disturbances and thereby make it more difficult to interpret the location and interconnection of the water-bearing zones.

On the basis of the results of the aforementioned hydraulic measurements, the expectation model will once again be updated and the location and length of the deposition tunnels will be determined.

Before the deposition tunnels are blasted out, tracers will be injected in the sealed-off sections in the pilot boreholes.

The deposition tunnels will be mapped after blasting very carefully, with rock type variations, fractures and other structures being recorded. Information on rock stresses and associated rock mechanics data, transmissive zones, hydraulic conductivity and water composition will be added to these data. This integrated information constitutes the basis for an initial assessment of the properties of the near field.

The rock around the deposition tunnels shall be disturbed as little as possible in connection with the excavation work. Full-face boring should be considered, but controlled blasting is assumed to be the preferred method. Tests of the disturbed zone around the deposition tunnels caused by blasting and stress redistribution will probably be conducted in the hard rock laboratory. However, the results of the ongoing investigations at Stripa should be presented before any further planning.

### Deposition holes

The integrated information from the excavation of the deposition tunnels will provide a basis for the positioning of the deposition holes. According to the KBS-3 system, these holes are 1.5 metres in diameter and 7.5 metres deep. The holes are spaced at intervals of six metres. Before final determination of the location of these holes, vertical pilot boreholes will be drilled in the tunnel floor for the planned positions. The nature of the bedrock will determine how many pilot holes are to be drilled, but pilot holes will probably not be needed for every deposition hole. (The number of deposition holes in a deposition tunnel is dependent in part on the subsequent investigation "Pilot tests, repository systems".)

Radar and hydraulic measurements will be carried out in the cored holes, supplemented with tunnel radar to obtain information on the bedrock between the pilot holes. In addition, samples will be taken for analysis of the composition of the water and previously injected tracers.

After processing and compilation of obtained data, a decision will be made regarding the location of the deposition holes. However, the drilling of each deposition hole will be preceded by a pilot borehole, which will be tested to the same extent as previously drilled pilot holes. If acceptable results are obtained, the deposition hole will be drilled.

Each deposition hole will be mapped, water-sampled and tested hydraulically with a special outfit. The data obtained will constitute grounds for the final verdict regarding the deposition hole. If there is any doubt as to the suitability of the hole, it will not be used for deposition.

## C 6.4 Predictions

The predictions are a direct continuation of the expectation models on different scales prepared according to Appendices A and B.

## C 6.5 Evaluation

All data obtained from the investigation will be compiled in descriptive models and compared with the expectation models where they indicate intervals within which obtained data is expected to lie. The final evaluation will result in a model that describes the current and expected future properties of the rock mass.

## C 6.6 Reporting of Results

A written report will be submitted before a decision is made regarding the location of deposition tunnels and deposition holes.

## C 6.7 Construction Works

Starting from a main tunnel with a cross-sectional area of about 25 m$^2$, four subhorizontal cored holes with an approximate length varying between 50 and 125 metres must be drilled. Four tunnels varying in length between 30 and 100 metres are also required. The cross-sectional area of these tunnels is estimated at about 20 m$^2$. The cored pilot holes in the deposition tunnels will be drilled to a depth of 10 metres and are estimated to number 19 (3 + 3 + 3 + 10), while the deposition holes are estimated to number 11 (2 + 2 + 2 + 5). All cored holes should have a diameter of 56–76 mm. The deposition holes should be on a natural scale in one of the deposition tunnels, ie 1.5 metres. The detailed design of the galleries will be determined in the mid-90s. Blasting will take place in the third construction stage at the end of the 90s.

## C 6.8 Preparatory Work

Equipment for hydraulic measurements in very large holes (up to 1.5 metres in diameter) must be developed.

In addition, a large number of non-sorbing tracers is needed.

Finally, some form of "criteria" for acceptable properties – individual or integrated – should be discussed so that a decision can be made as to what is "sound" and what is "unsound" rock.

# C 7 PILOT TESTS, REPOSITORY SYSTEMS

The programme described below is based on the assumption that the KBS-3 concept is finally chosen. This concept has been selected as an example to permit the tests to be described in some detail. Most of the proposed tests are, however, also relevant if alternative systems such as horizontal deposition tunnels or the VDH concept (Very Deep Holes) should finally be chosen. The aim of the test is to study the interaction between rock and buffer.

## C 7.1 Background and Current State of Knowledge

The physical properties and chemical resistance of several well-defined buffer materials will be known in detail at the time of the field tests in the Hard Rock Laboratory. Single and coupled models for their conductivity, diffusivity, rheological and thermomechanical behaviour, as well as their tendency towards mineral alteration as a consequence of the hydrothermal processes in a disposal facility, will also be formulated. This makes it possible on theoretical grounds to predict heat, water, gas and ion transport as well as mechanical action in the composite system buffer/rock in each phase after the sealing of a disposal facility. The influence of various less probable scenarios should also be able to be predicted. These models make it possible to determine the most suitable repository concept and to effect a technical/economic optimization of the finally chosen concept.

It has been possible to test the individual functions of the buffer materials experimentally in the laboratory and at Stripa, but it has not been possible to document the interaction between buffer and rock under the temperature influences of the kind that will be present in a disposal facility at the water pressures and water pressure gradients that occur in such a facility. Effects of various rock movements on buffer and canister in the natural environment with residual stresses have not been tested. Nor has there been an opportunity to perform full-scale tests on the models for diffusion of corrosion products and radionuclides in the near field that are of such importance from the safety-assessment viewpoint. The Hard Rock Laboratory provides good opportunities for such tests.

## C 7.2 Goals

The goal of the field research concerning buffer/rock in the Hard Rock Laboratory is to validate models and demonstrate function by clarifying the interaction between rock and finally chosen buffers under conditions prevailing in disposal facilities. Another purpose is to develop and test methods and strategies for their application.

The sub-goals will be affected by the ongoing work being conducted within the frame of the Stripa project, for example. The following sub-goals can be specified at this time:

- Testing of method for selection of suitable locations for deposition holes and tunnels and application of the most suitable method for drilling with a view towards how the drilling affects the function of the rock (Drilling method was tested in preparatory R&D). See also Section C 6.
- Documentation of the effect of promising methods for blocking and diversion of groundwater flow in "the disturbed zone", ie in the immediate vicinity of tunnels and shafts under actual pressure conditions.
- Testing of the thermomechanical behaviour of the system of heated canister surrounded by highly compacted smectite clay and rock (measurement of subsidence/heave of canisters, lifting of tunnel floors

and influence on the hydraulic conductivity of the near field as a consequence of swelling pressure and temperature impact).
- Verification of the concept for critical gas pressure when a steel canister is surrounded by highly compacted smectite clay (measurement of gas pressure, STEM on the clay).
- Verification of rheological models for mechanical long-term action on the clay buffer and its interaction with rock and canister (swelling, compression, homogenization, creep, rock movements).
- Demonstration of method for full-scale application in deposition holes.
- Full-scale application of suitable method for effective packing of tunnel backfill and its interaction with surrounding rock shall be tested in preparatory R&D.

The tests are of importance for the main goals: "To further develop and demonstrate design, planning and construction" and "To collect material and data for safety assessment" and tie in with the stage goals: "To demonstrate construction and handling methods" and "To test important parts of the repository system".

## C 7.3 Execution, Predictions and Evaluations

The programme has been divided into ten sub-tests that indicate the thrust of the experiment.

### Sub-test 1 "Characterization of the near field"

This is the first activity. It will demonstrate how characterization of the near field can be carried out during repository construction. A detailed description is provided in Section C 6.

### Sub-test 2 "Treatment of the disturbed zone"

Identification and treatment of conductive zones of importance for the buffer tests will be done during preparation of test tunnels. The work may entail the creation of grouting shields. In the Hard Rock Laboratory, the arrangements will be provided with extensive piezometry equipment for documenting the effect of the sealing measures under the prevailing high water pressures.

Prior to execution of the test, a prediction will be made of the effects of the measures as regards the change of the pressure and flow situation around the tunnels. The results can be evaluated by measuring the pressure and flow around the tunnels before and after the measures.

### Sub-test 3 "Characterization of the immediate near field, sealing"

Characterization of the immediate near field surrounding the canister hole and assessment of injection-grouting needs, plus injection grouting will then take place. Drilling of full-sized deposition holes and characterization of the near field will then be done after which a comparison will be made between forecast and reality with respect to fracture systems and groundwater flux. It may involve a total of ten large holes to be used for subsequent investigations.

### Sub-test 4 "Thermomechanics"

The subsidence/heave of canisters and surrounding rock will be measured in two of the large holes in a realistic heating/ cooling scenario. Prediction will be made of the thermomechanical course of events, with such factors as fracture geometry around the holes serving as input data. The results can be evaluated by measurement of temperature, water pressure and deformations in rock and buffer material.

### Sub-test 5 "The gas concept"

After water saturation of the bentonite, gas pressure will be induced at the canister periphery at normal temperature and at high temperature. The critical gas pressure and the gas penetration paths in the rock will be predicted and evaluated.

### Sub-test 6 "Rheological rock-buffer interaction"

Possible events in deposition holes will be simulated. These will be preceded by model-based predictions, providing a comparison and validation of the calculation models. Such a scenario may be rock shear with residual high stresses and resultant creeps. Another scenario may be swelling and homogenization of the smectite clay from a deposition hole into large rock fractures or openings. A third scenario may be to study the effects of initially extremely nonhomogeneous smectite clay in deposition holes.

### Sub-test 7 "Application of bentonite and canister"

The method for applying a heated canister, surrounded by highly compacted bentonite in block form in deposition holes, will be demonstrated. This will be done on a full scale with the final choice of geometry and material.

### Sub-test 8 "Tunnel backfill"

In a separate gallery without deposition holes, backfill of a suitable composite type (crushed rock/bentonite) will be compacted by means of a method tested in preparatory R&D. The gallery will be sealed with a sturdy wall backed by a grouting shield so that high water pressures can be built up. Extensive piezometry installations will be done to document the pressure buildup expected to result from sealing of the disturbed zone. The investigation will be performed at normal temperature.

The water flow rate in the rock and the buffer mass and the pressure buildup in the rock will be predicted and evaluated.

## C 7.4 Documentation

In addition to regular status reports, a final report shall be submitted on each preparatory experiment and each subtest on completion of the test. A summary of results and conclusions and a synthesis of the interaction rock/buffer shall be done at the end of the entire project.

## C 7.5 Construction Works

The investigation requires four galleries. Two of the galleries shall about 50 metres long and the others about 25 metres long. In addition, approximately ten deposition holes with a diameter of 1.5 metres and a depth of 8-10 metres have to be drilled. Since the tests are to be carried out with infiltration of different substances and pressurization of water-filled boreholes, the distance to other test stations must be sufficiently great. An underground laboratory and a computer centre with a total floor area of about 5 x 15 metres should be built at the openings of the four galleries. Some slits and a large number of boreholes are also included in the required rock works.

## C 7.6 Preparatory Work

The preparatory work includes three main elements:

- Detailed planning of the tests and verification of program codes. This cannot be done until the disposal method has been chosen in the mid-90s.
- Development of method for drilling of deposition holes in accordance with the KBS-3 concept requires new technology and an analysis of how the primary stress field and the induced stresses in the surrounding rock affect fracture width and fracture continuity.
- Development of method for compaction of tunnel backfill.