International Progress Report

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Äspö Hard Rock Laboratory

Planning Report for 2002

Svensk Kärnbränslehantering AB

June 2002

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The Äspö Hard Rock Laboratory, Planning Report for 2002

This report presents the planned activities for year 2002 with background, objectives, experimental concepts (where applicable), and scope of work. It details the programme for the Äspö Hard Rock Laboratory described in SKB's Research, Development and Demonstration Programme 2001, and serves as a basis for the management of the laboratory. The plan is revised annually.

This time the Planning Report is issued very late, caused by the ambition to structure Äspö's Planning, Status and Annual Reports in a transparent way. Each report will have a specific role, so that information in common is less repeated in the future. Each report shall contain enough information for providing an adequate background to the reader, but not to the level where each report can stand-alone. The role of the Planning Report is to present the background and objectives of each experiment. Thereby the Status Reports may concentrate on work in progress and refer to the Planning Report for more background information. The Annual Report will in detail present new findings and results, and will only include necessary background information.

This year a first attempt is made to give each report a specific role. It is not fully implemented and need to be refined. Comments from the reader are most helpful in this process.

Svensk Kärnbränslehantering AB

Repository Technology

Christer Svemar
Director

Executive summary

General

The Äspö Hard Rock Laboratory (HRL) constitutes an important part of SKB's work to design and construct a deep geological repository for spent nuclear fuel and to develop and test methods for characterisation of a suitable site.

One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 450 m.

SKB's overall plans for research, development, and demonstration during the period 2002-2007 are presented in SKB's RD&D-Programme 2001. The planned activities related to Äspö HRL are detailed on a yearly basis in the Äspö HRL Planning Report and an overview of main activities for 2002 is given below. The Äspö HRL and the associated research, development, and demonstration tasks, managed by the Repository Technology Department within SKB, has so far attracted considerable international interest.

Natural Barriers

At the Äspö HRL experiments are performed at conditions that are expected to prevail at repository depth. The experiments are related to the rock, its properties, and in-situ environmental conditions. The goals are to increase the scientific knowledge of the safety margins of the deep repository and to provide data for performance and safety assessment.

Tests of models for groundwater flow, radionuclide migration and chemical/biological processes are one of the main purposes of the Äspö HRL. The programme includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models.

The main projects are Tracer Retention Understanding Experiments (TRUE), Long Term Diffusion Experiment, Radionuclide Retention Experiment with CHEMLAB, Microbial Project, Colloid Project, and Matrix Water Chemistry.

Tracer tests are carried out in the TRUE-projects. These are conducted at different scales; laboratory scale (< 0.5 m), detailed scale (~ 5 m) and block scale (~ 50 m) with the aim to identify flow paths, retention of weakly and moderately sorbing tracers and the effect of matrix diffusion. Experiments in the laboratory and detailed scales have been completed and reported, and the tracer test stage of the TRUE Block Scale will come to its conclusion during the first half of 2002. Complementary field works and modelling are currently performed in two projects: TRUE-1 Continuation and TRUE Block Scale Continuation.

A Long Term Diffusion Experiment is performed to investigate diffusion of solutes, during 3-4 years, from natural fractures into matrix rock. The aim is to improve the understanding of sorption processes and obtain sorption data for some radionuclides on natural fracture surfaces. The rockwork at the site is concluded and pre-tests, installation of equipment, as well as injection of tracers are planned activities during 2002. Modelling of the experiments is being done by several groups associated to the Äspö Task Force for Modelling of Groundwater Flow and Transport of Solutes.

Radionuclide Retention Experiments are carried out with the aim to confirm results of laboratory studies in-situ, where natural conditions prevail concerning e.g. contents of colloids, organic matter, and bacteria in the groundwater. The experiments are carried out in special borehole probes, CHEMLAB 1 and CHEMLAB 2, designed for different kinds of in-situ experiments. Experiments can be carried out in simulated near field conditions (bentonite) and in tiny rock fractures. The focus during year 2002 is on the influence of radiolysis products on the migration of the redox-sensitive element technetium in bentonite in CHEMLAB 1 and on experiments with redox-sensitive transuranics in a rock fracture in CHEMLAB 2.

In the Colloid Project the concentration, stability, and mobility of colloids in the Äspö environment is studied. The project also comprises studies of the potential of colloids to enhance solute transport and the potential of bentonite clay as a source for colloid generation. During year 2002 background measurements of colloid concentrations at Äspö and laboratory experiments are to be concluded and reported. Field experiments to study bentonite clay, as a source for colloid generation will be initiated during this year.

The Microbe Project has been initiated in the Äspö HRL for studies of microbial activity in groundwater at in-situ conditions. Microbial effects on redox conditions, radionuclide migration, gas composition, and gas consumption will be in focus. At the 450 m level, the development of a formation groundwater circulation system and a system for sensible measurement of hydrogen and other reducing gases has been set up. The field experiments are planned to be up and running during the second half of 2002.

The main objectives of the Matrix Fluid Chemistry experiment are to understand the origin and age of matrix fluids in fissures and small-scale fractures and their possible influence on fluid chemistry in the bedrock. Matrix fluids are sampled from a borehole drilled into the rock matrix. Fluid inclusions in core samples have also been studied. The gathering of scientific data has almost been conducted and reported and the main activities during 2002 aim at final reporting of the whole project. However, a continuation is under consideration.

An important goal for the activities at Äspö HRL includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models. An important part of this work is performed in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. The work in the Task Force is closely tied to ongoing and planned experiments at the Äspö HRL. Specified tasks are defined where several modelling groups work on the same set of field data. The modelling results are then compared to the experimental outcome and evaluated by the Task Force delegates. Currently active tasks are coupling between hydrochemistry and hydrogeology (Task 5) and performance assessment modelling using site characterisation data (Task 6). Task 5 is finalised during 2002, while Task 6 is new and under development.

Further modelling work includes the development of codes (NUMMOD) for groundwater flow and transport that will be undertaken and applied to Äspö data.

Demonstration of technology for and function of important parts of the repository system

The Äspö HRL makes it possible to demonstrate and perform full-scale tests of the function of different components of the repository system that are important for the performance and the long-term safety of a repository. It is also important to show that high quality can be achieved in design, construction, and operation of the repository. To fulfil these task several projects are performed, e.g. Demonstration of Repository Technology, Prototype Repository, Backfill and Plug Test, Canister Retrieval Test, Long Term Tests of Buffer Material, and Pillar Stability Experiment.

The project of Demonstration of Repository Technology provides a full-scale example of canister deposition under radiation shielded conditions and works with testing of canister handling in full size deposition holes. Testing and demonstration of the deposition process is ongoing, e.g. in the Prototype Repository.

The Prototype Repository is located in the last part of the TBM tunnel at the 450 m level and will include six deposition holes in full scale. The aims of the Prototype Repository are to demonstrate the integrated function of the repository components and to provide a full-scale reference for comparison with models and assumptions. The Prototype Repository should, to the extent possible, simulate the real deep repository system, regarding geometry, materials, and rock environment. Instrumentation will be used to monitor processes and properties in the canister, buffer material, backfill and the near-field rock. The installations in the inner section were completed and the plug, which seals off this inner part, was casted during 2001. Installations of the remaining two canisters in the outer section including backfill and casting of the end plug were originally planned to take place during 2002. However, the malfunction of the heaters will postpone the starting date and a new time plan will be established once the means of handling the heater problem has been decided upon.

The Backfill and Plug Test has the aim to test different backfill materials, emplacement methods and full-scale plugging. It is also a test of the hydraulic and mechanical function of the backfill materials and their interaction with the near field rock. During 1999 the experimental set-up was finished, the tunnel was backfilled, and the plug to seal the drift put in place. The wetting of the backfill materials started in the end of 1999 and has continued during the years 2000 and 2001. The water pressure was increased during 2001 to enhance the water saturation of the backfill and will be increased further during 2002. The wetting of the backfill will continue until full saturation is obtained and testing of backfill properties will start thereafter. If the wetting rate agrees with predictions, flow testing of the backfill can start during 2003. Supplementary laboratory tests and modelling work are planned during 2002 to increase the understanding of the water saturation process.

In the Canister Retrieval Test two full-scale deposition holes have been drilled for the purpose of testing technology for retrieval of canisters after the buffer has become saturated. These holes have also been used for comprehensive studies of the drilling process and the rock mechanical consequences of drilling the holes. Canister and bentonite blocks were emplaced in one of the holes during 2000, the hole was sealed with a plug, heater turned on and artificial water supply to saturate the buffer started. Problems with short-circuit in the electrical system of the heaters occurred in the end of 2001. However, it has been possible to provide the needed experimental conditions and so far (end of May 2002) the heating has continued without problem. The plan is to continue the artificial water supply and the heating until the bentonite buffer has been fully saturated.

The Long Term Tests of Buffer Material aim to validate models and hypotheses concerning physical properties in a bentonite buffer and of related processes such as bentonite degradation, microbiology, copper corrosion and gas transport in buffer material under conditions similar to expected repository conditions. Five 300 mm diameter test holes have been drilled and instrumented. Five test parcels with different duration times were installed in 1999 and in 2001 the 1-year parcel was extracted from the rock by overlapping core-drilling. The remaining four test parcels are planned to run for at least five years. The main task during 2002 is to examine the field-exposed material from the 1-year parcel. Water pressure, total pressure, temperature and moisture in the four remaining parcels are continuously being measured and the results will be analysed and reported.

A Pillar Stability Experiment has been initiated to complement an earlier study performed at URL in Canada. The major aims are to demonstrate the capability to predict spalling in fractured rock mass and the effect of backfill on the propagation of micro cracks. In addition the capabilities of 2D and 3D mechanical and thermal predictions will be compared. A feasibility study and preliminary design of the experiment were completed during 2001. The main activities during 2002 are predictive modelling and site characterisation.

A project, in co-operation with Posiva, concerning the use of low-alkali cementitious products in the deep repository began in 2001. The objectives of the project are to develop recipes for cementitious products to be used as grouting and mortar for anchoring of rock bolts and to demonstrate the usage of these products in small field experiments in Äspö HRL. The field experiments will be performed during 2002.

Late 2001 SKB published an R&D program for KBS-3H, a variant of KBS-3 with horizontal deposition of the canisters. The R&D program is divided into four parts: Feasibility study, Basic design, Construction and testing at the Äspö HRL, and Evaluation. The feasibility study was initiated during 2001 and will be concluded during 2002. It will be followed by a decision concerning the continuation of the project in accordance with the R&D program, which is carried through by SKB in co-operation with Posiva.

A project with the aims to identify and to demonstrate, in field experiments, the best available techniques for cleaning and sealing of investigation boreholes will be initiated in 2002. The first phase, that comprises identification of available techniques, complementary laboratory experiments with potential sealing materials, and investigation of the status of two boreholes at Äspö that are planned to be used for the demonstration of cleaning techniques, will be concluded in 2002.

A Task Force on Engineered Barrier Systems has also been initiated. The preparatory workshop suggested that the prior focus should be on the water saturation process in buffer, backfill and near-field rock. Since the water saturation process is also a part of the modelling work in the Prototype Repository, the work of the Task Force was consequently linked together with modelling work within the EC-project concerning the Prototype Repository.

Äspö facility

The main goal for the operation of the facility is to provide a safe and environmentally correct facility for everybody working or visiting the Äspö HRL. This includes preventative and remedy maintenance in order to withhold high availability in all systems as drainage, electrical power, ventilation, alarm and communications in the underground laboratory.

An important part of the Äspö facility is the administration, operation, and maintenance of instruments as well as development of investigation methods. Other tasks are the program for monitoring of groundwater head and flow and the program for monitoring of groundwater chemistry with respect to time and space within the Äspö HRL.

The aim of the GeoMod project is to update existing geological, geomechanical, geohydrological and hydrogeochemical models over Äspö by integrating new data collected since 1995, as well as by integrating the different geoscientific models compiled separately before. A major part of the new data has been collected during the operational phase for the different experiments. The new data have been produced in the lower part of the Äspö HRL. The updated model will focus on a volume including the tunnel spiral volume from about 340 m to about 500 m.

International co-operation

Eight organisations from seven countries are from January 2002 participating in the Äspö HRL. The co-operation is based on separate agreements between SKB and the organisations in question. Most of the organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several organisations are participating in the experimental work as well as in the Äspö Task Force on modelling of groundwater flow and transport of solutes.

SKB is through Repository Technology co-ordinating two EC contracts: Prototype Repository and Cluster Repository Project (CROP). SKB takes part in several EC projects of which the representation in five projects is channelled through Repository Technology: FEBEX II, BENCHPAR, ECOCLAY II, SAFETI and PADAMOT.

Contents

1 General

1.1 Background

The Äspö Hard Rock Laboratory (HRL), in the Simpevarp area in the municipality of Oskarshamn, constitutes an important part of SKB's work to design and construct a deep geological repository for spent nuclear fuel and to develop and test methods for characterisation of a suitable site. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. Most of the research is focused on processes of importance for the long-term safety of a future deep repository.

The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 450 m, see Figure 1-1. The total length of the tunnel is 3600 m where the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The first part of the tunnel has been excavated by conventional drill and blast technique. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts.

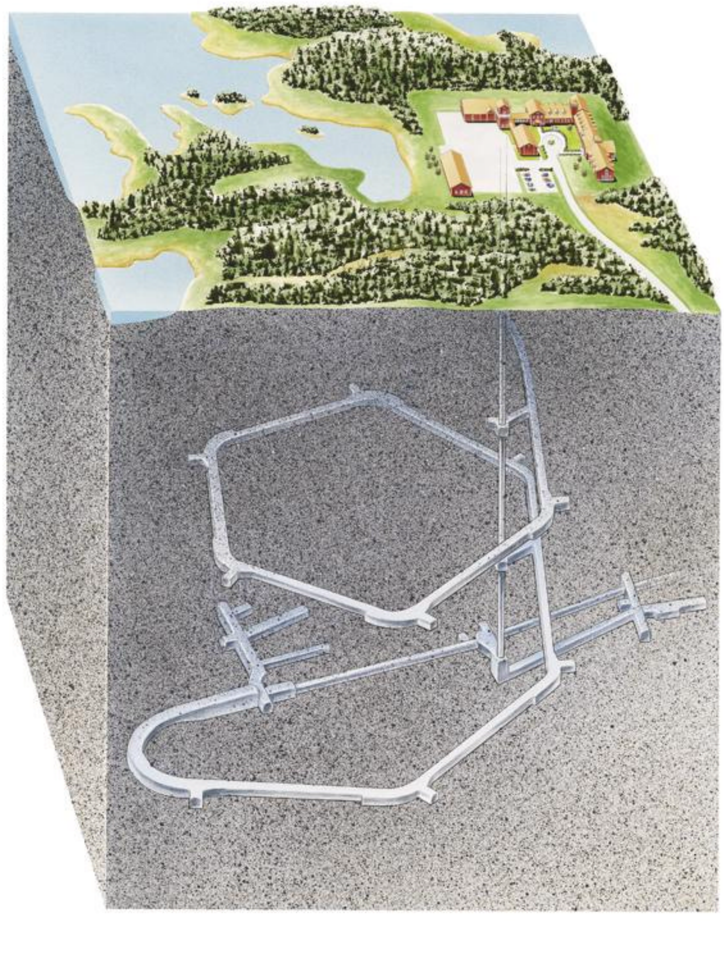

Figure 1-1. *Overview of the Äspö HRL facilities.*

The work with Äspö HRL has been divided into three phases: Pre-Investigation Phase, Construction Phase, and Operational Phase.

During the **Pre-Investigation Phase**, 1986-1990, studies were made to provide background material for the decision to locate the laboratory to a suitable site. The natural conditions of the bedrock were described and predictions made of geological, hydrogeological, geochemical etc. conditions to be observed during excavation of the laboratory. This phase also included planning for the Construction and Operational Phases.

During the **Construction Phase**, 1990-1995, comprehensive investigations and experiments were performed in parallel with construction of the laboratory. The excavation of the main access tunnel to a depth of 450 m and the construction of the Äspö Research Village were completed.

The **Operational Phase** began in 1995. A preliminary outline of the program for this phase was given in SKB's Research, Development and Demonstration (RD&D) Programme 1992. Since then the program has been revised every third year and the basis for the current program is described in SKB's RD&D-Programme 2001 /SKB, 2001a/.

1.2 Goals

To meet the overall time schedule for SKB's RD&D work, the following stage goals were initially defined for the work at the Äspö HRL.

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.

2. **Finalise detailed investigation methodology**. Refine and verify the methods and the technology needed for characterisation of the rock in the detailed site investigations.

3. **Test models for description of the barrier functions at natural conditions**. Further develop and at repository depth test methods and models for description of groundwater flow, radionuclide migration, and chemical conditions during operation of a repository and after closure.

4. **Demonstrate technology for and function of important parts of the repository system.** Test, investigate and demonstrate on full-scale different components of importance for the long-term safety of a deep repository and to show that high quality can be achieved in design, construction, and operation of repository components.

Stage goals 1 and 2 has been concluded at Äspö HRL and the tasks are transferred to the Site Investigation Department of SKB which, when this report goes into print, has began site investigations at two sites, Simpevarp in the municipality of Oskarshamn and Forsmark in the municipality of Östhammar.

In order to reach the goals the following important tasks are performed at the Äspö HRL:

- Develop, test, evaluate and demonstrate methods for repository design and construction, and deposition of spent nuclear fuel and other long-lived waste.

– Develop and test alternative technology with the potential to reduce costs and simplify the deep repository concept without sacrificing quality and safety.

– Increase the scientific understanding of the deep repository's safety margins and provide data for safety assessments of the long-term safety of the repository.

– Provide experience and train personnel for various tasks in the deep repository.

– Provide information to outsiders on technology and methods that are being developed for the deep repository.

1.3 Organisation

The current organisation of SKB is shown in Figure 1-2. The organisation is set up to provide a focus of activities and use of resources to meet SKB's main near term goal, which is to perform site investigations. Site investigations, including drilling, should commence in 2002. The strategy to reach this goal is described in a supplementary report to the RD&D Report 1998 focusing of the issues of repository method, site selection process and site investigation activities, dated December 2000 /SKB, 2000/.

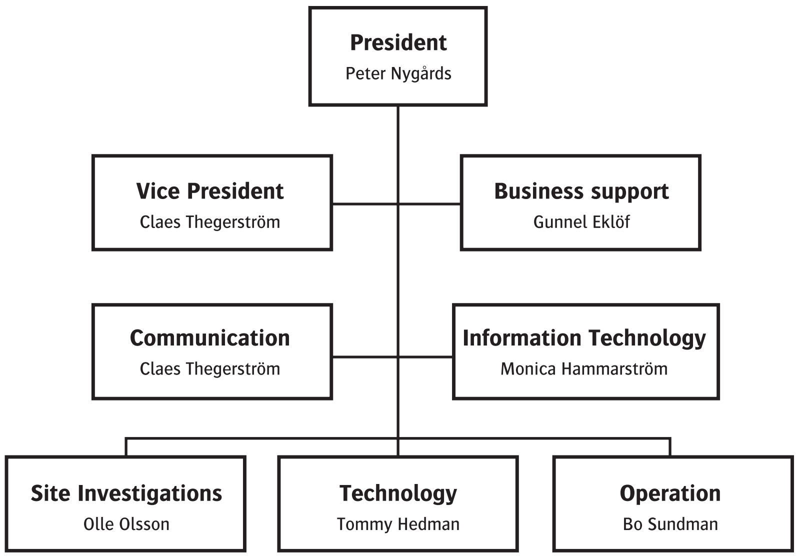

Figure 1-2. *SKB's current organisation.*

SKB's work is organised into three departments; Site Investigations, Technology, and Operation. All research, technical development, and safety assessment work is organised into one department – Technology, in order to facilitate co-ordination between the different activities. The Technology department is organised into five units:

– *Safety and Science (TS)* is responsible for research, safety assessments, and systems analysis.

– *Repository Technology (TD)* is responsible for development and testing of deep repository technology and in-situ research on repository barriers at natural conditions. The unit is also responsible for the operation of the Äspö facility and the co-ordination of the research performed in international co-operation.

– *Encapsulation Technology (TI)* is responsible for development and testing of the copper canister and the design of the Encapsulation Plant. This unit is also responsible for the operation of the Encapsulation Laboratory located in Oskarshamn.

– *Large Projects (TP)* is responsible for large construction projects. Presently the main task of this unit is the construction of CLAB 2 – the expansion of CLAB to a total storage capacity of 8000 tons of spent nuclear fuel.

– *Repository Design (TU)* is responsible for the design and layout of the deep repository. Presently site specific layouts are being developed for the two sites where site investigations are being performed. This department is also responsible for development of the technology needed to build, operate and seal the repository.

1.3.1 Repository Technology and Äspö Hard Rock Laboratory

The Repository Technology unit is organised in three operative groups, see Figure 1-3:

– *Technology and Science* is responsible for the co-ordination of projects undertaken at the Äspö HRL, for providing service (design, installations, measurements etc.) to the experiments undertaken at Äspö HRL, to manage the geo-scientific models of the "Äspö Rock Volume", and to maintain knowledge about the methods that have been used and the results that have been obtained from work at Äspö HRL.

– *Facility Operation* is responsible for operation and maintenance of the Äspö HRL offices, workshops and underground facilities, and for operation and maintenance of monitoring systems and experimental equipment at Äspö.

– *Administration, QA and Economy* is responsible for providing administrative service and quality systems.

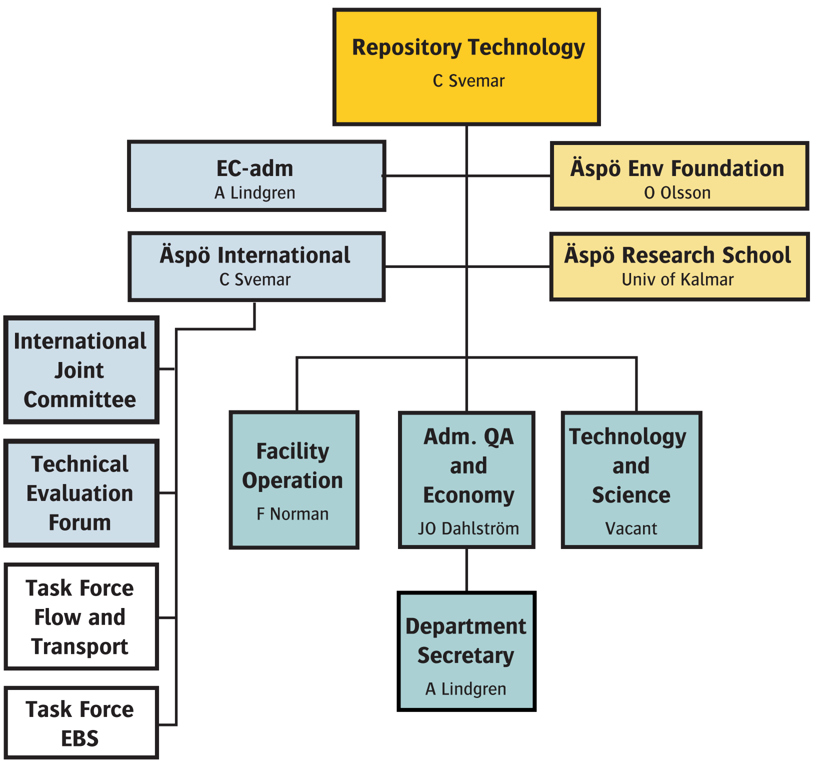

Figure 1-3. *Organisation of Repository Technology and Äspö HRL.*

The Äspö Hard Rock Laboratory and the associated research, development, and demonstration tasks are managed by the Director of Repository Technology. The International co-operation at the Äspö Hard Rock Laboratory is the responsibility of the Director of Repository Technology and SKB's International Co-ordinator, Torsten Eng.

Each major research and development task is organised as a project that is led by a Project Manger who reports to the head of Technology and Science group. Each Project Manager will be assisted by an On-Site Co-ordinator from the Site Office with responsibility for co-ordination and execution of project tasks at the Äspö HRL. The staff at the Site Office provides technical and administrative service to the projects and maintains the database and expertise on results obtained at the Äspö HRL.

1.3.2 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. Eight organisations from seven countries are from January 2002 participating in the Äspö HRL in addition to SKB. The participating organisations are:

- Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA), France.
- Bundesministerium für Wirtschaft und Technologie (BMWi), Germany.
- Central Research Institute of Electric Power Industry (CRIEPI), Japan.
- Empresa Nacional de Residuos Radiactivos (ENRESA), Spain.
- Japan Nuclear Cycle Development Institute (JNC), Japan.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA),Switzerland.
- Posiva Oy, Finland.
- United States Department of Energy, Carlsbad Field Office (USDOE CBFO).

For each partner the co-operation is based on a separate agreement between SKB and the organisation in question. The co-operation with the Japanese organisations is performed under one agreement. JNC is the official representative within the co-operation.

The international partners and SKB reached a joint decision to form the Äspö International Joint Committee (IJC). IJC is responsible for the co-ordination of the work arising from the international participation. The committee meets once every year. In conjunction with each IJC meeting a Technical Evaluation Forum (TEF) is held. TEF consists of scientific experts appointed by each organisation.

For each experiment the Äspö HRL management establishes a Peer Review Panel consisting of three to four Swedish or International experts in fields relevant to the experiment.

Specific technical groups, so called Task Forces, are another form of organising the international work. A Task Force on Groundwater Flow and Transport of Solutes in fractured rock has been working since 1992 and a Task Force on Engineered Barrier Systems has been initiated by IJC.

Some EC projects are co-ordinated by the Director of Repository Technology and administrated by the Repository Technology staff. Examples are EC projects concerning the Prototype Repository that has a direct coupling to the test set-up at Äspö, the CROP project that is coupled to experiments carried out in the Äspö HRL, and PADAMOD that has a strong coupling to radionuclide retention.

1.4 Allocation of experimental sites

The rock volume and the available underground excavations have to be divided between the experiments performed at the Äspö HRL. It is essential that the experimental sites are allocated so that interference between different experiments is minimised. The allocation of experimental sites within the Äspö HRL is shown in Figure 1-4.

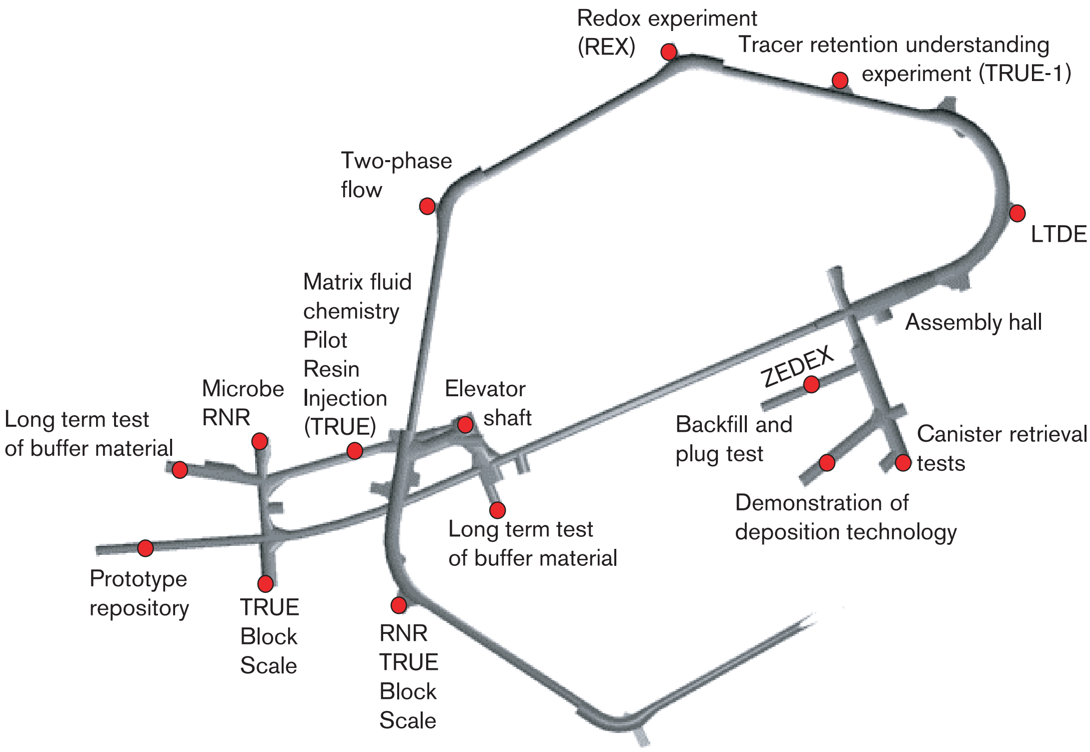

Figure 1-4. Underground excavations at the 300-450 m levels and allocation of experimental sites.

1.5 Reporting

Äspö HRL is an important part of SKB's RD&D-Programme. The plans for research and development of technique during the period 2002-2007 are presented in SKB's RD&D-Programme 2001.

The information given in the RD&D-Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report. The plan is revised annually and the current report gives an overview of the planned activities for the calendar year 2002. Detailed account of achievements to date for the Äspö HRL can be found in the Äspö HRL Annual Reports that are published in SKB's Technical Report series. In addition, Status Reports are prepared four times a year for internal distribution.

Joint international work at Äspö HRL as well as data and evaluations for specific experiments and tasks are reported in Äspö International Progress Reports (IPR). Information from Progress Reports is summarised in Technical Reports (TR) at times considered appropriate for each project. SKB also endorses publications of results in international scientific journals. In order to facilitate quick distribution of results

Technical Documents (ITD) are prepared. The Technical Documents constitute working material and are not distributed to third parties. Table 1-1 provides an overview of Äspö HRL related documents and the policy for review and approval.

Data collected from experiments and measurements at Äspö HRL are mainly stored in SKB's site characterisation database, SICADA.

Table 1-1. Overview of Äspö HRL related documents.

Report	Reviewed by	Approved by
SKB RD&D-Programme - Äspö HRL related parts	Director Repository Technology	SKB
Planning Reports – Detailed plans covering each calendar year	Contributors	Director Repository Technology
Annual Reports - Summary of work covering each calendar year	Repository Technology unit	Director Repository Technology
Status Reports - Short summary of work covering each 3 month period	Principal Investigators Project Managers	Director Repository Technology
Technical Reports (TR)	Project Manager	Director Repository Technology
International Progress Reports (IPR)	Project Manager	Director Repository Technology
Technical Documents (ITD)	Case-by-case	Project Manager

1.6 Management system

SKB is since 2001 certified according to the Environmental Management System ISO 14001 and also to the Quality Management Standard ISO 9001.

The structure of the management system is based on procedures, handbooks, instructions, identification and traceability, quality audits etc. The overall guiding document for issues related to management, quality and environment are written as routines. The documentation can be accessed via SKB's Intranet, where policies, common routines for SKB as well as specific routines for Äspö HRL can be found.

Employees and contractors related to the SKB organisation are responsible that works will be performed in accordance with SKB's management system.

1.7 Structure of report

The information given in SKB's RD&D-Programme related to Äspö HRL is detailed on a yearly basis in the Äspö HRL Planning Report.

The planned work in Äspö HRL during 2002 is described in four chapters in this report:

– Natural barriers – experiments, analysis and modelling to increase the knowledge of the repository barriers under natural conditions.

– Demonstration of technology for and function of important parts of the repository system.

– Äspö facility – operation, maintenance, data management, and monitoring etc.

– International co-operation.

2 Natural barriers

2.1 General

At the Äspö HRL experiments, with the aim to increase the knowledge of the long-term function of the repository barriers, are performed at conditions that are expected to prevail at repository depth. The bedrock with available fractures and fracture zones, its properties and on-going physical and chemical processes which affect the integrity of the engineered barriers and the transport of radionuclides are denoted the natural barriers of the deep geological repository for radioactive wastes. The experiments are related to the rock, its properties, and in-situ environmental conditions. The strategy for the on-going experiments is to concentrate the efforts on those experiments which results are needed for site investigations. This focus implies the need to involve experts of different geoscientific disciplines into the work in order to facilitate integration and spread information.

Tests of models for groundwater flow, radionuclide migration and chemical/biological processes are one of the main purposes of the Äspö HRL. The programme includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models.

The overall purposes are to:

- Improve the scientific understanding of the deep repository's safety margins and provide input data for assessments of the repository's long-term safety.
- Obtain the special material needed to supplement data from the site investigations in support of an application for a siting permit for the deep repository.
- Clearly present the role of the geosphere for the barrier functions: isolation, retardation and dilution.

Isolation is the prime function of a deep geological disposal system such as the KBS-3 repository. Isolation is obtained through the co-function of the natural and engineered barriers. The flow of water to the waste containment is largely determining the magnitude at which the corrosion of the canister and the dissolution of the waste form can take place. For a good isolation it is thus necessary to minimise the groundwater flow to the waste containment. Additional conditions that affect the isolation are the chemistry of the groundwater and the mechanical stability of the rock.

Retention of radionuclides is the second most important barrier function of the repository. Retention is provided by physical and chemical processes and will be provided by any system and process that interacts with radionuclides dissolved in the groundwater. Some elements are strongly retarded while others are escaping with the flowing groundwater.

Dilution is the third barrier function. It will take place in the rock volume surrounding the repository. The magnitude of dilution is very much depending on the site specific conditions. In the geosphere the dilution is caused by the dispersion in groundwater. No experiment at Äspö is focussing on dilution, although dilution is included in the biosphere safety assessment modelling.

The concluded, ongoing or planned experiments with in the Natural Barriers at Äspö HRL are:

- Tracer Retention Understanding Experiments (TRUE).
- Long Term Diffusion Experiment (LTDE).
- Radionuclide Retention Experiments with CHEMLAB.
- Microbial Project (MICROBE).
- Colloid Project (COLLOID).
- Matrix Fluid Chemistry (MATRIX).

In addition, to the experiments conceptual and numerical models for groundwater flow and solute transport have been developed through the entire Äspö Project. During 2002 the focus is on further development of the numerical tools used for groundwater flow and transport calculations. A major part of this work will be within the Äspö Task Force on Groundwater Flow and Transport of Solutes modelling work (Task 6).

The activities planned during 2002 for each experiment or task are described in the following sections.

2.2 Tracer Retention Understanding Experiments

Background

A programme has been defined for tracer tests at different experimental scales, the so-called Tracer Retention Understanding Experiments (TRUE) /Bäckblom and Olsson, 1994/. The overall objective of the defined experiments is to increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock, and to increase the credibility in models used for radionuclide transport calculations, which will be used in licensing of a repository.

The basic concept is that tracer experiments will be performed in cycles with an approximate duration of 3-4 years. At the end of each test cycle, results and experiences will be evaluated and the programme revised.

Objectives

The TRUE experiments should achieve the following general objectives:

- Improve understanding of radionuclide transport and retention in fractured crystalline rock.
- Evaluate to what extent concepts used in models are based on realistic descriptions of rock and whether adequate data can be collected during site characterisation.
- Evaluate the usefulness and feasibility of different approaches to modelling radionuclide migration and retention.
- Provide in-situ data on radionuclide migration and retention.

Experimental concept

The basic idea of the experiments is to perform a series of in-situ tracer tests with progressively increasing complexity. In principle, each tracer experiment will consist of a cycle of activities beginning with geological characterisation of the selected site, followed by hydraulic and tracer tests, after which epoxy resin will be injected in the rock volume. Subsequently the tested rock volume will be excavated and analysed with regards to flow-path geometry and tracer concentration.

Together with supporting laboratory studies of diffusion and sorption characteristics made on core samples, the results of the in-situ tests will provide a basis for integrating data on different scales, and testing of modelling capabilities for radionuclide transport up to a 100 m scale, see Figure 2-1.

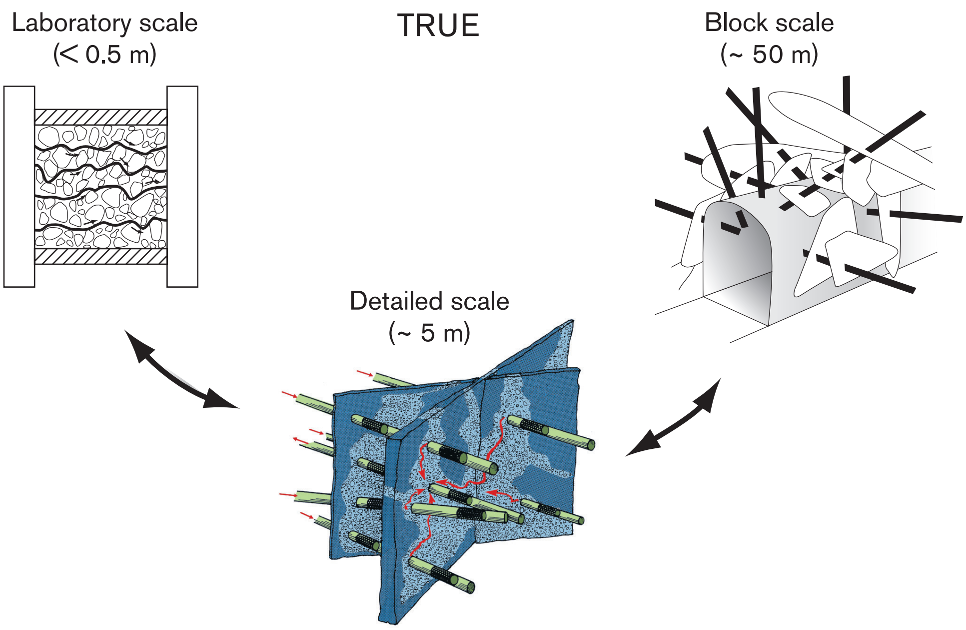

Figure 2-1. *Schematic representation of transport scales addressed in the TRUE programme.*

Present status

The first in-situ experiment, TRUE-1, performed on a detailed scale, was of limited duration in time, and was primarily aimed at technology development, although including comprehensive tracer tests using radioactive sorbing tracers. A final report on the First TRUE Stage has been published /Winberg et al., 2000/. The experiments conducted during the First TRUE Stage have also been subject to predictions and evaluations using an assortment of different modelling concepts within the framework of the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes /Elert, 1999, Elert and Svensson, 2001/. In September 2001 the 4th International Äspö Seminar was held fully devoted to discussion of the TRUE-1 data and results as well as relevant studies from elsewhere /SKB, 2001b/.

The initial test cycle was originally planned to be followed by a second series of tracer tests in the detailed scale, of longer duration, and allowing full address of different retention mechanisms. However, due to resource priorities this stage (initially denoted TRUE-2) has been postponed indefinitely.

An experiment in the block scale, the so-called TRUE Block Scale, has been in progress since 1996 and will come to its conclusion during the second half of 2002, see Section 2.2.1.

Complementary field-work in the block scale is performed in the TRUE Block Scale Continuation project and work in the detailed scale is performed at the TRUE-1 site in the TRUE-1 Continuation project, see Sections 2.2.2 to 2.2.4.

2.2.1 TRUE Block Scale

The block scale (~ 50 m) completes the sequence of scales addressed within the TRUE programme which also include detailed scale (~ 5 m) and laboratory scale (< 0.5 m). The TRUE Block Scale project is an international partnership funded by ANDRA, ENRESA, Nirex, Posiva, JNC and SKB.

Objectives

The objectives of the TRUE Block Scale experiment /Winberg, 1997/ are to:

- Increase the understanding and the ability to predict tracer transport in a fracture network.
- Assess the importance of tracer retention mechanisms (diffusion and sorption) in a fracture network.
- Assess the link between flow and transport data as a means for predicting transport phenomena.

Present status

During the time-period 1996 through 1999 five boreholes have been drilled, characterised and completed with multi-packer systems. The possibility to perform well-controlled (high mass recovery) block scale tracer tests in a fracture network has been demonstrated /Winberg et al, 2000/. The results of the performed characterisation has resulted in a focus on a particular fracture network (defined by Structures #20, #13, #21, #22 and #23) for the subsequent tracer tests, see Figure 2-2.

The tracer test were performed in three phases (A-C) and are now being evaluated and reported. Phase A /Andersson et al., 2000a/ focused on identification of suitable injection sections and sink sections, Phase B /Andersson et al., 2000b/ was to demonstrate mass recovery and matrix diffusion, and Phase C comprised a series of four injections with radioactive tracers.

During the course of the project the hydrostructural model of the major deterministic structures within the studied block has been updated at five occasions.

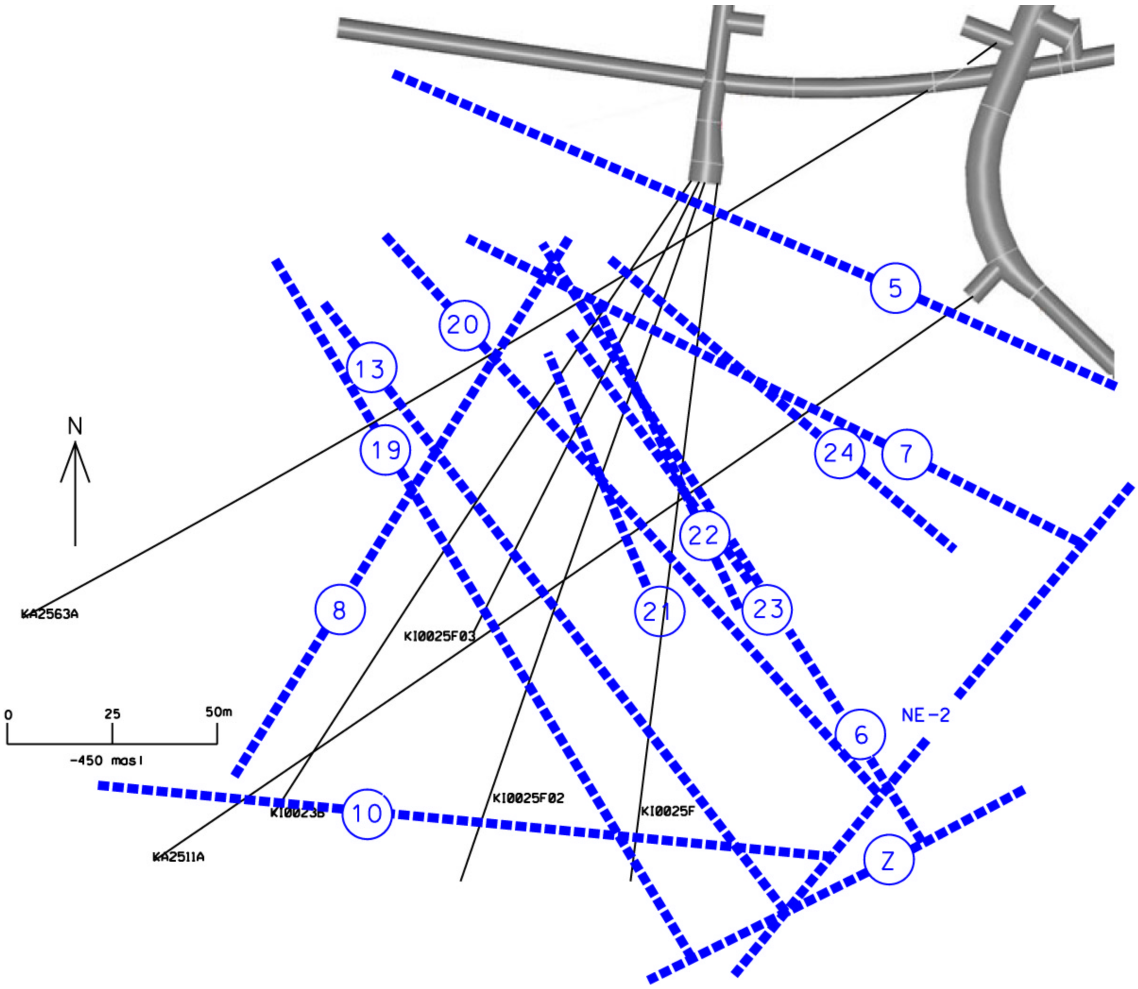

__Figure 2-2.__ Plan view of the Tracer Test Stage hydro-structural model with focus on the target volume of the block /Hermanson and Doe, 2000/.

The official TRUE Block Scale experiments are completed. The pumping and sampling of the TRUE Block Scale will however continue, see Sections 2.2.2 and 2.2.3.

Scope of work for 2002

Work on the final evaluation and reporting is under way and is expected to be completed during 2002. The TRUE Block Scale project will be reported in a series of four final reports:

- Characterisation and model development.
- Tracer tests in the block scale.
- Modelling of flow and transport.
- Synthesis of flow, transport and retention in the block scale.
- 1st International TRUE Block Scale Seminar at Äspö HRL (November, 2002).

2.2.2 Continuation of tracer retention understanding experiments

During 2000, it was decided to collect all future TRUE work in two separate projects; TRUE Block Scale Continuation and TRUE-1 Continuation

The overall objectives for both projects are to:

– Demonstrate and validate a process for defining the critical geologic element(s) for flow and transport/retention and their properties.

– Define, at different scales, the pore space (responsible for/necessary to explain) transport, diffusion, sorption and loss of tracer.

– Integrate experimental results from laboratory scale, detailed scale and block scale to obtain a consistent and adequate description of transport, to serve as a basis for modelling transport from canister to biosphere.

2.2.3 TRUE Block Scale Continuation

The TRUE Block Scale Continuation (BS 2) has its main focus on the existing TRUE Block Scale site. The TRUE Block Scale Continuation is divided into two separate phases:

BS 2a Continuation of the TRUE Block Scale (Phase C) pumping and sampling including employment of developed enrichment techniques to lower detection limits. Complementary modelling work which includes evaluation of tails of breakthrough curves, evaluation of simplified examples related to heterogeneity in flow and retention parameters, formulation of new hypotheses to be tested by in-situ experiments.

BS 2b Additional in-situ tracer tests based on BS 2a analysis. Tests preceded by reassessment of the need to optimise/remediate the piezometer array. The specific objectives of BS 2b are to be formulated on the basis of the outcome of BS 2a.

Scope of work for 2002

The work planned is mainly:

– Compilation of data from the continued TRUE Block Scale Phase C (injections with radioactive tracers) in a database and a report. The compilation constitutes a basis for complementary modelling.

– Complementary modelling with the aim to define new hypothesis to be tested with tracer tests (TRUE Block Scale site).

– Optimisation of installations in the boreholes e.g. packer positions.

2.2.4 TRUE-1 Continuation

The TRUE-1 Continuation is a continuation of TRUE-1. The 4th International Äspö Seminar (focused on the First TRUE Stage) re-emphasised the need for conducting the planned injection of epoxy resin at the TRUE-1 site. However, before conducting such an impregnation, some complementary cross-hole hydraulic interference tests combined with tracer dilution tests are foreseen. These tests are intended to shed light on the possible three-dimensional aspects of transport at the site. The planned tests would employ both previously used sink sections and some not employed in the already performed tests. A complication for the scheduling of planned work lies in the fact that the TRUE-1 and LTDE sites (see Section 2.3) are hydraulically connected. In view of the urge for a relative hydraulic tranquillity on the part of LTDE, a priority for advancing LTDE has been set by SKB. Consequently, the resin impregnation at the TRUE-1 site will be postponed. According to the present plans injection will be possible late 2004.

Objectives

The objectives of TRUE-1 Continuation are:

- To obtain insight into the internal structure of the investigated Feature A, in order to allow evaluation of the pore space providing the observed retention in the experiments performed.
- To provide insight into the three-dimensionality of the rock block studied as part of the First TRUE Stage such that the role and effects of the fracture network connected to Feature A on the performed tracer tests can be assessed.
- Test methodology to assess fracture aperture from radon concentration in groundwater and radon flux from geological materials.

The scope of identified remaining field activities at the TRUE-1 site includes:

- Complementary cross-hole interference and tracer dilution /tracer tests with conservative trace.
- Test of methodology to estimate fracture aperture (from radon concentration in groundwater and radon flux estimates from geological materials).
- Injection of epoxy resin into the previously investigated Feature A, with subsequent excavation and analyses.

During the past year a pre-study was conducted with the objective of investigating the need and practical limitations for optimising the experimental array at the TRUE-1 site. In addition time series of groundwater head, inflow to relevant tunnel sections and selected groundwater chemistry components were compiled from the onset of the TRUE-1 investigations till present. A re-instrumentation of borehole KXTT4 was conducted which resulted in improved isolation of Feature A.

During the 4th quarter groundwater sampling for analyses of radon concentration in groundwater was performed at two different occasions.

Scope of work for 2002

- Complementary cross-hole, tracer dilution and tracer tests at the TRUE-1 site.
- Analysis of radon emission from different geological materials (gouge and wall rock.
- Planning of resin injection work (techniques, hardware, and radiation safety aspects).

Plans will also be developed for (a) laboratory experiments on retention on breccia/gouge material and (b) in-situ impregnation of fault rock zones, special emphasis on porosity of fault gouge.

2.3 Long Term Diffusion Experiment

Background

The Long Term Diffusion Experiment (LTDE) constitutes a complement to performed diffusion and sorption experiments in the laboratory, and a natural extension of the experiments conducted as part of TRUE-1 and TRUE Block Scale. The difference is that the longer duration (3-4 years) of the experiment is expected to enable an improved understanding of diffusion and sorption in the vicinity of a natural fracture surface.

Matrix diffusion studies using radionuclides have been performed in several laboratory experiments and also in-situ. Some experimental conditions such as pressure and natural groundwater composition are however difficult to simulate in laboratory experiments. Investigations of rock matrix diffusion in laboratory scale imply that one uses rock specimens in which damage due to drilling and unloading effects (rock stress redistribution) may have caused irreversible changes of the rock properties. Matrix diffusion in non-disturbed rock is therefore preferably investigated in-situ. Through the proposed experimental technique one will also obtain some information of the adsorption behaviour of some radionuclides on exposed granitic rock surfaces.

Scooping calculations for the planned experiment have been performed /Haggerty, 1999/ using the multi-rate diffusion concept which accounts for pore-scale heterogeneity. A test plan was drafted and presented at the combined TRUE-2/LTDE review meeting in March 1999. The review and desires of SKB redirected the experiment towards an assessment of diffusion from a natural fracture surface, through the altered zone into the intact unaltered matrix rock. The new direction resulted in a revision of the test plan from its final form /Byegård et al, 1999/.

Objectives

The objectives of the Long Term Diffusion Experiment project are:

- To investigate diffusion into matrix rock from a natural fracture in-situ under natural rock stress conditions and hydraulic pressure and groundwater chemical conditions.
- To improve the understanding of sorption processes and obtain sorption data for some radionuclides on natural fracture surfaces.
- To compare laboratory derived diffusion constants and sorption coefficients for the investigated rock fracture system with the sorption behaviour observed in-situ at natural conditions, and to evaluate if laboratory scale sorption results are representative also for larger scales.

Original experimental concept

A core stub of 50 mm length with a natural fracture surface is isolated in the bottom of a large diameter telescoped borehole. A cocktail of non-sorbing and sorbing tracers are circulated in the test section for a period of 3-4 years after which the core stub is overcored, and analysed for tracer content and tracer fixation.

The experiment is planned to focus on a typical conductive fracture identified in a pilot borehole (KA3065A02) drilled within the context of the SELECT-2 project. A telescoped large diameter borehole (300/196.5 mm) is to be drilled sub-parallel to the pilot borehole in such away that it intercepts the identified fracture some 10 m from the tunnel wall and at an approximate separation of 0.3 m between the mantel surfaces of the two boreholes, leaving a 50 mm long core stub in the borehole.

The stub is sealed off with a polyurethane cylinder and a peek lid, which constitutes a "cup-like" packer. The remainder of the borehole will be packed off with a system of one mechanical and two inflatable packers. The system of packers and an intricate pressure regulating system will be used to eliminate the hydraulic gradient along the borehole.

During the circulation of tracer, samples of water will be collected at various times over the duration of the experiment. The redox situation in the circulation loop will be monitored continuously with a flow through cell, which will measures pH, Eh (three different electrodes) and temperature. After completion of tracer circulation, the core stub is over-cored, sectioned and analysed for tracer content.

The project also involves a variety of mineralogical, geochemical and petrophysical analyses. In addition, as in the REX project, a "replica" laboratory through diffusion experiment is planned on the corresponding "stub" material.

Characterisation

The drilling of the telescoped large diameter experimental borehole was performed with a high degree of interactivity between; careful iterative drilling in short uptakes (particularly in the inner part of the borehole), BIPS imaging, core examination and on-site structural modelling/updating of structural model. Despite these precautions, and due to poor visibility caused by degassing, which seriously impaired the BIPS imaging, and the fact that a critical part of the core immediately adjacent to the target structure fell out of the core barrel at the bottom of the borehole, the resulting stub turned out three times longer than originally planned, i.e. 150 mm.

The situation was analysed in a series of in-situ and laboratory measurements, which were compared with existing in-situ Äspö data/results and results in the literature. The performed in-situ measurements included endoscope video imaging of the walls of the core stub in the 9.75 mm cylindrical slot between the core stub and the borehole wall. In addition the experimental borehole and the stub surface were documented by analogue video using a remote controlled vehicle. The results showed no macroscopic fractures on the walls of the stub. The inflow points along the boreholes established in a tentative way from the video recordings were correlated with the drilling records, BIPS and core logs. The location of inflow points was subsequently established in more detail using single packer flow logging. The laboratory work, apart from basic mineralogy and geochemistry along the pilot and experimental boreholes, included micro-seismic measurements on drill cores, and thin sections analyses in various directions, the latter two measurements aimed at quantifying the degree of sample disturbance on the core. Performed mechanical modelling and performed measurements indicate that no, or insignificant disturbance due to formation of new micro fractures is to be expected. However, opening of existing grain boundaries and widening of existing micro fractures will occur throughout the core stub.

Modified experimental concept

This situation, described above, in combination with a growing concern that axial diffusion through the core stub may effectively be occurring in the damaged core stub alone, initiated work on alternative/modified experimental concepts.

The modified experimental concept presented to SKB included provision of access to unaltered and intact wall rock by drilling a 36 mm borehole, axially and centralised, through the face of the core stub and about 1 m into the rock. Through this option the possibility to study sorption/axial diffusion in the vicinity of a natural fracture surface is retained. In addition, the possibility to study radial diffusion in an unaltered intact wall rock is secured. A schematic drawing of the telescopic borehole with the stub and the surface and down-hole equipment is shown in Figure 2-3. The adaptation of the original borehole instrumentation was found to be achievable through minor modifications including addition of two mechanical 36 mm packers.

The 36 mm extension of the borehole was drilled early October 2001. Comprehensive planning proceeded the drilling and development of the drilling procedure and updating of the descriptive structural model based on KA3065A02 and KA3065A03. The resulting structural model is shown in Figure 2-4.

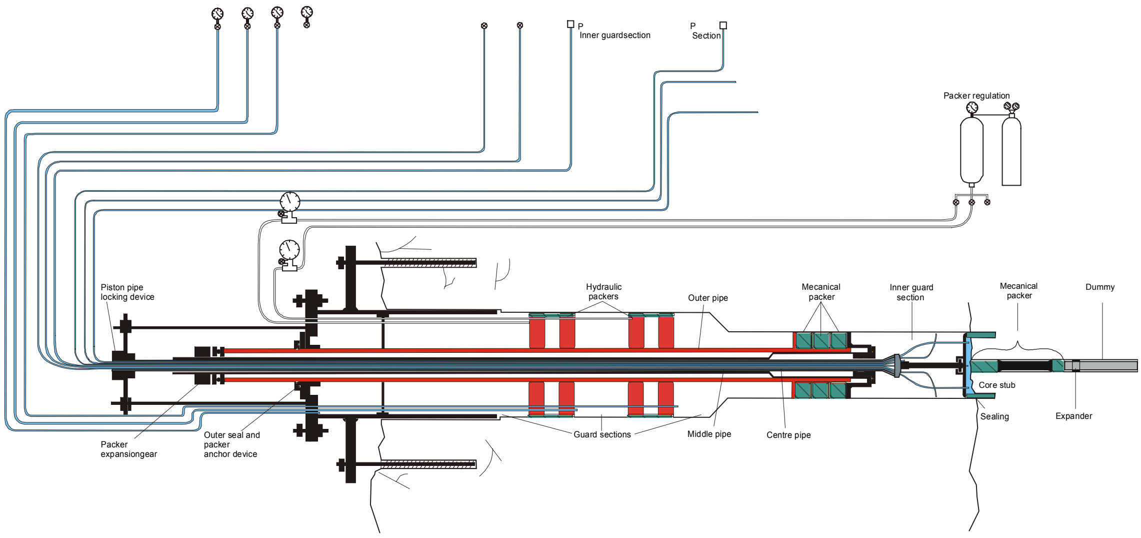

Figure 2-3. *Schematic drawing showing the modified down-hole equipment in the telescoped larger diameter LTDE borehole.*

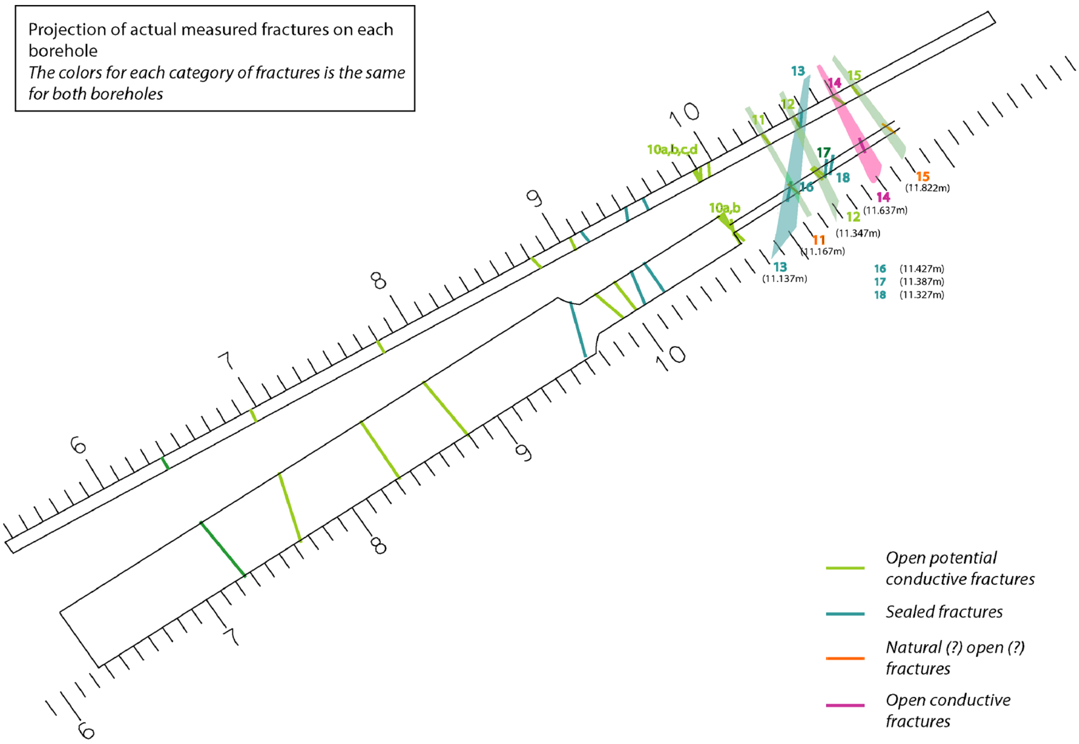

Figure 2-4. *Plane view of interpreted structures in the interior of experimental telescoped borehole KA3065A03.*

Present status

The present status can be summarised as:

- Slim hole in the centre of the core stub has been successfully completed.
- Slim hole has been characterised and an update of the descriptive geological model is under way.
- The problem associated with a leaky casing (in the outer part of the borehole) is identified and various grouting techniques are being considered to remediate the problem.
- Complementary down-hole equipment for the slim hole is being constructed and manufactured.
- Manufacturing and pre-arrangement of equipment hosted in experimental container e.g. manufacturing of epoxy glove boxes, chemical flow through cells (pH, Eh, temperature etc.) are under way.

Scope of work for 2002

Planned activities are:

- Manufacturing and testing of equipment for the 36 mm extension of the borehole in the centre of the core stub.
- Remeadiation of leaky casing.
- Installation of borehole equipment.
- Performance of pre-tests in the array of surrounding boreholes (pressure monitoring and interference tests in experimental borehole sections and in surrounding borehole array, testing of leakage scenarios for tracers, establishment of chemically stable conditions).
- Start of circulation followed by injection of tracers.
- Start of laboratory tests on replica material (porosity, mineralogy etc.).
- Continuation of work with CE-marking of experimental set-up.

2.4 Radionuclide Retention Experiments

Background

Laboratory studies on the solubility and migration of long-lived nuclides e.g. Tc, Np, and Pu indicate that these elements are so strongly sorbed on the fracture surfaces and into the rock matrix that they will not be transported to the biosphere until they have decayed. This very strong retention could well be an irreversible sorption process.

Laboratory studies of radionuclide retention under natural conditions are extremely difficult to conduct. Even though the experiences from different scientists are uniform it is of great value to be able to demonstrate the results of the laboratory studies in-situ, where the natural contents of colloids, of organic matter, of bacteria etc. are present in the groundwater used in the experiments. A special borehole probe, CHEMLAB, has been designed for different kinds of in-situ experiments where data can be obtained representative for the properties of groundwater at repository depth.

The results of experiments in CHEMLAB will be used to validate models and check constants used to describe radionuclide dissolution in groundwater, the influence of radiolysis, fuel corrosion, sorption on mineral surfaces, diffusion in the rock matrix, diffusion in buffer material, transport out of a damaged canister and transport in an individual fracture. In addition, the influence of naturally reducing conditions on solubility and sorption of radionuclides will be tested.

Objectives

The objectives of the radionuclide retention experiments are:

- To validate the radionuclide retention data which have been measured in laboratories by data from in-situ experiments.
- To demonstrate that the laboratory data are reliable and correct also at the conditions prevailing in the rock.
- To decrease the uncertainty in the retention properties of relevant radionuclides.

Experimental concept

CHEMLAB is a borehole laboratory built into a probe, in which in-situ experiments can be carried out under ambient conditions with respect to pressure and temperature, and with the use of natural groundwater from the surrounding rock. Initially one "all purpose" unit, CHEMLAB 1, was constructed in order to meet any possible experimental requirement. At a later stage, a simplified version the CHEMLAB 2 unit was designed to meet the requirements by experiments where highly sorbing nuclides are involved. Figure 2-5 illustrates the principles of the CHEMLAB 1 and CHEMLAB 2 units.

In the currently ongoing or already completed experiments the following are studied:

- Diffusion of cations (Cs^+, Sr^{2+} and Co^{2+}) and anions (I^-, TcO_4^-) in bentonite.
- The influence of primary and secondary formed water radiolysis products on the migration of the redox-sensitive element technetium.
- Migration of actinides (americium, neptunium and plutonium) in a rock fracture.

Diffusion in bentonite

In the diffusion experiments compacted clay is placed between two filters in an experimental cell in CHEMLAB. A small volume of solution prepared from filtrated Äspö water and spiked with the radionuclide(s) used as tracers is transferred to the tracer reservoir. The tracers are; ^{57}Co in the first experiment, ^{134}Cs and ^{85}Sr in the second experiment, and ^{131}I and ^{99}Tc in the third experiment. After preparation of CHEMLAB 1 the sond, packers etc. are placed in a borehole in Äspö HRL.

Radiolysis experiments

Reduced technetium will be placed in a diffusion cell containing bentonite. In the experiment with primary formed water radiolysis products the technetium tracer is placed on an irradiation source at the bottom of the cell. In the experiment with secondary formed products the technetium tracer will be placed inside the cell while an irradiation source will be placed outside the cell.

Migration of actinides

Experiments on the migration of actinides, americium, neptunium and plutonium, in a natural rock fracture in a drill core are carried out in the CHEMLAB 2.

The rock samples are analysed with respect to the flow-path and to the actinides sorbed onto the solid material. Non-destructive and destructive techniques will be applied, such as x-ray computer tomography and cutting the samples after injection of fluorescent epoxy resin. The distribution of actinides along the flow-path will be determined from the abraded material gained by cutting, as well as by coupled laser ablation ICP-MS techniques of the slices.

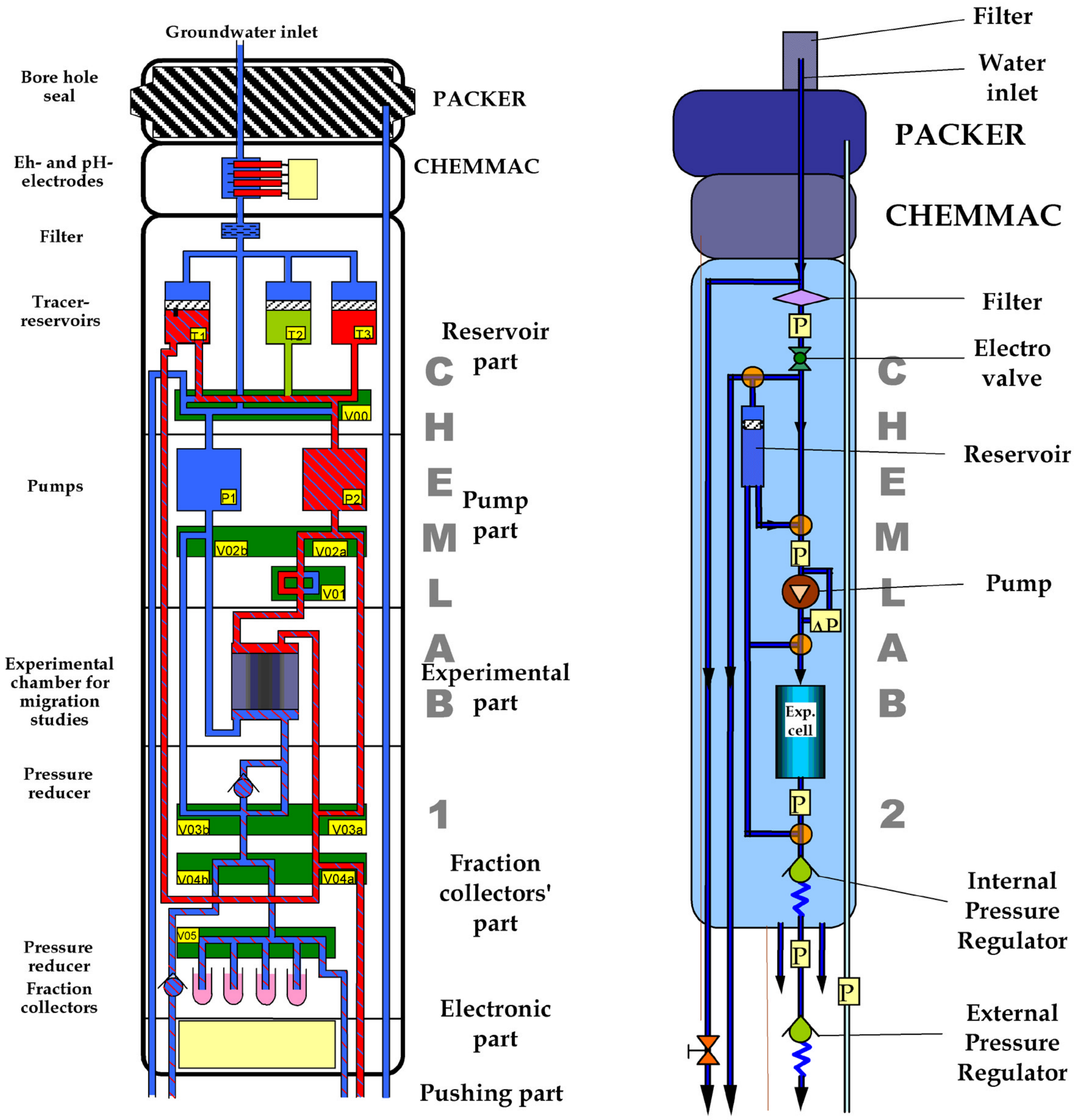

Figure 2-5. Schematic illustration of CHEMLAB 1 and 2.

Present status

Diffusion in bentonite

Experiments on diffusion of cations (Co^{2+}, Sr^{2+} and Cs^{+}) and anions (I^{-} and TcO_4^{-}) in compacted bentonite clay have been carried out with the CHEMLAB 1 unit. The cations and the anion (I^{-}) behaved as expected from the laboratory investigations, but in spite of strongly reducing condition technetium was found to diffuse unreduced. The evaluation of the diffusion experiments are available in a final report /Jansson and Eriksen, 2001/.

Radiolysis experiments

The radiolysis experiments, in CHEMLAB 1, are intended to investigate the influence of radiolysis on the migration of oxidised technetium in bentonite clay. Due to delays in the final evaluation of the experiments on diffusion in bentonite, the start of the radiolysis experiments has been postponed.

Actinide experiments

During fall 2000 the first of several actinide migration experiments at Äspö were performed. Due to a failure in CHEMLAB 2 the first actinide experiment was stopped in advance, the results have not yet been evaluated.

Scope of work for 2002

The radiolysis experiments are planned to start in March 2002.

The second experiment with actinides will be run during 2002 and the third actinide migration experiment is scheduled to start as soon as the second experiment has been evaluated.

2.5 Colloid Project

Background

Colloids are small particles in the size range 10^{-3} to 10^{-6} mm. The colloidal particles are of interest for the safety of a repository for spent nuclear fuel because of their potential to transport radionuclides from a defect waste canister to the biosphere.

SKB has for more than 10 years conducted field measurements of colloids. The outcome of those studies performed nationally and internationally concluded that the colloids in the Swedish granitic bedrock consist mainly of clay, silica and iron hydroxide particles and that the mean concentration is around 20-45 ppb which is considered to be a low value /Laaksoharju et al., 1995/. The low colloid concentration is controlled by the attachment to the rock, which reduces both the stability of the colloids and their mobility in aquifers.

It has been argued that e.g. plutonium is immobile owing to its low solubility in groundwater and strong sorption onto rocks. Field experiments at the Nevada Test Site, where hundreds of underground nuclear tests were conducted, indicate however that plutonium is associated with the colloidal fraction of the groundwater. The $^{240}Pu/^{239}Pu$ isotope ratio of the samples established that an underground nuclear test 1.3 km north of the sample site is the origin of the plutonium /Kersting et al., 1999/.

The findings of potential transport of solutes by colloids and access to more sensitive instruments for colloid measurements motivated a Colloid Project at Äspö HRL The project was initiated by SKB in 2000 and is planed to continue until December 2003.

Objectives

The aims and objectives of the Colloid Project is to study:

- The stability and mobility of colloids.
- Measure colloid concentration in the groundwater at Äspö.
- Bentonite clay as a source for colloid generation.
- The potential of colloids to enhance radionuclide transport.

The results from the project will be used mainly in the future development of safety assessment modelling of radionuclide migration.

Experimental concept

The Colloid Project comprises: laboratory experiments, background measurements, borehole specific measurements and fracture specific measurements.

Laboratory experiments

The role of the bentonite clay as a source for colloid generation at varying groundwater salinity (NaCl/CaCl) is studied in laboratory experiments. Bentonite clay particles are being dispersed in water solutions with different salinity and the degree of sedimentation is studied, see Figure 2-6. The experiment has been extended to investigate in detail the chemical changes and size distribution associated with colloid generation.

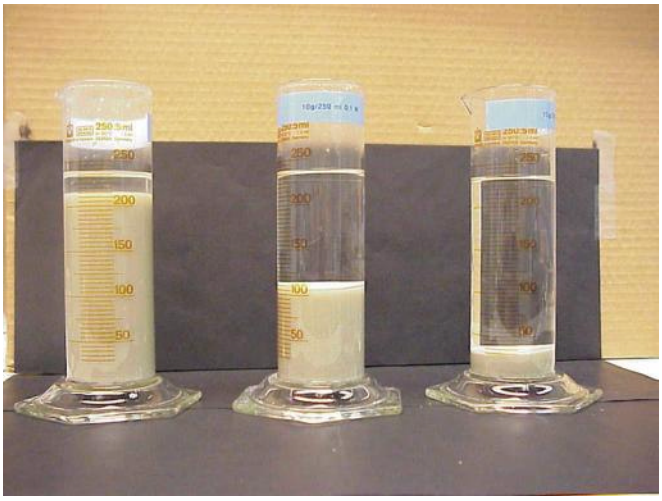

Figure 2-6. *The salinity of the water can influence the colloid concentration. The experiment shows different degrees of sedimentation of bentonite dissolved in water at different ionic strengths (NaCl) in the water. A high or low ionic strength can result in instability and colloid formation.*

Background measurements

The natural background colloid concentrations are measured from 8 different boreholes, representing groundwater with different ionic strength, along the Äspö HRL-tunnel.

The colloid content is measured on-line from the boreholes by using a modified laser based equipment LIBD (Laser-Induced Breakdown-Detection) which has been developed by INE in Germany, see Figure 2-7. The advantage is that the resolution of this equipment is higher compared with standard equipment. It is therefore possible to detect colloid content at low concentrations. The outcome of these measurements will be compared with standard type of measurements such as particle counting by using Laser Light Scattering (LLS) on pressurised groundwater samples. Standard type of filtration and ultra filtration was performed of the groundwater. In addition, samples for determination of groundwater composition, microbes and humic material are collected from the selected boreholes in order to judge the contribution from these on the measured colloid concentration. The electrical conductivity is measured along the tunnel from water venues in order to reflect the variability of the groundwater composition, which can affect the colloid stability.

Borehole specific measurements

The aim of the borehole specific measurements is to determine the colloid generation properties of bentonite clay in contact with groundwater. Three boreholes along the Äspö tunnel will be used for the borehole specific measurements. The boreholes are selected so that the natural variation in the groundwater composition at Äspö is covered. The groundwater in the borehole is in contact with bentonite clay adapted in a container/packer equipment in the borehole and the colloid content in the ground water is measured prior and after contact with the bentonite clay, see Figure 2-9. The colloid content is measured by using laser (LIBD/LLS) and conventional filtering.

Fracture specific experiment

A fracture specific measurement is planned within the Colloid Project. The design of this experiment is however dependent of the results from the other experiments in the project and a final judgement will be taken during the summer of 2002.

According to present plans two nearby boreholes intersecting the same fracture having the same basic geological properties will be selected for the fracture specific experiment at Äspö HRL. One of the boreholes will be used as an injection borehole and the down-stream borehole will be used for monitoring. After assessing the natural colloid content in the groundwater, bentonite clay will be dissolved in ultra pure water to form colloidal particles. The colloids are labelled with a lanthanide (e.g. Europium) and the fluid is labelled with a water conservative tracer. The mixture will be injected into the injection borehole, see Figure 2-8. The colloidal content will be measured with laser (LIBD/LLS), the water is filtered and the amount of tracers is measured. The result of major interest is the changes in colloid content prior and after the transport through the fracture. The outcome of the experiment will be used to check performed model calculations and to develop future colloid transport modelling.

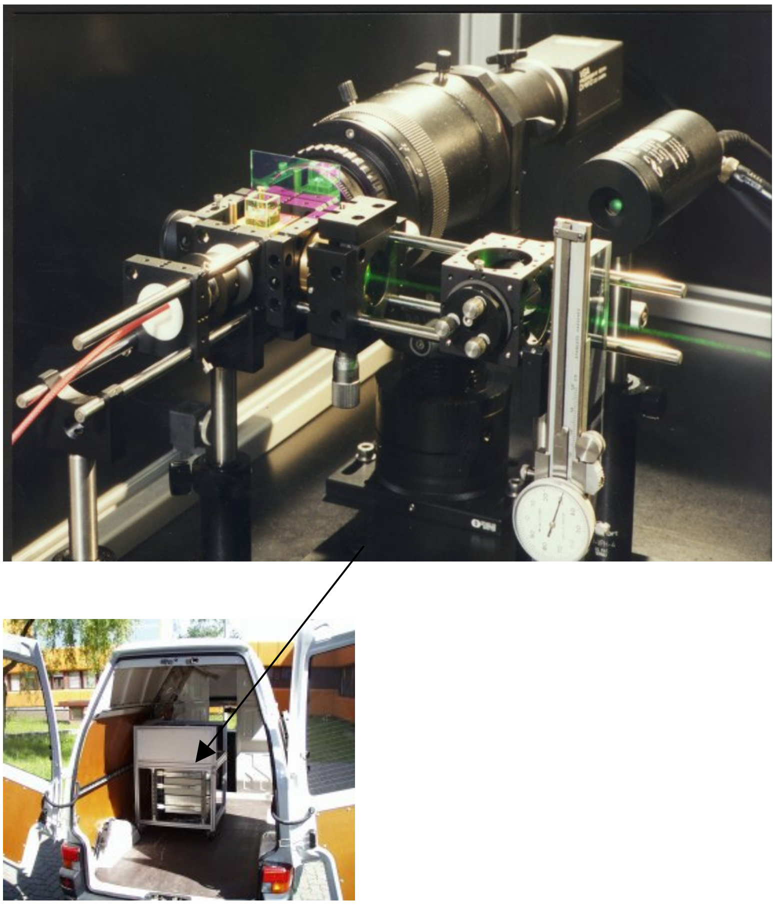

Figure 2-7. *Equipment for Lacer-Induced Breakdown-Detection (LIBD) of colloids (upper picture). The equipment is installed in a van in order to allow mobility and on-line measurements (lower picture).*

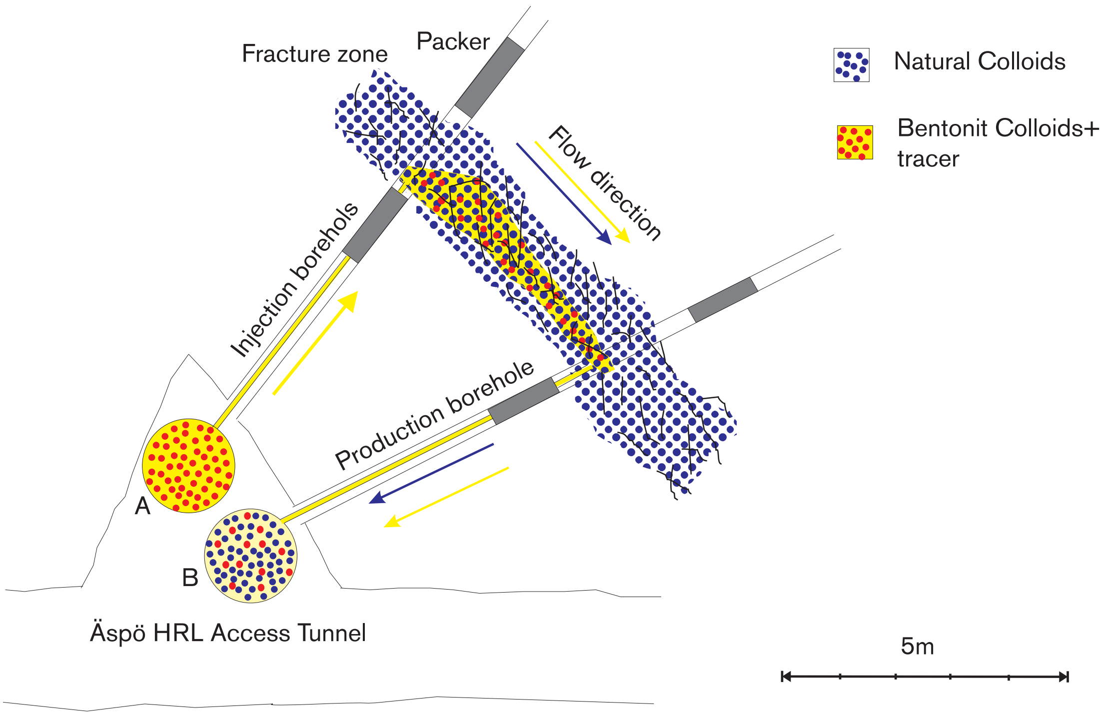

Figure 2-8. *Borehole specific measurement - injection of bentonite colloids and monitoring of the injected and natural colloids in the production borehole.*

Present status

The following topics have been carried out:

- The laboratory experiments were performed during the time-period August-December 2001 by KTH (Royal Institute of Technology, Stockholm) and a Swedish company Claytec.
- Background measurements were performed during the time-period October-November 2001. INE-team (Germany), Posiva-team (Finland) and SKB-team performed the work.

Scope of work for 2002

The scope of the work for 2002 comprises:

- The results from the laboratory experiments and the background measurements will be presented and discussed at the international Äspö Colloid workshop 5:th of March 2002 in Stockholm.
- The results from the laboratory experiments and background measurements will be compiled in a final report at the end of 2002.
- Planning, construction of equipment, testing, preparations and carrying out the field-work for the borehole specific measurements. The field activity is planned during the time-period April-August 2002.
- Decision concerning the design of the fracture specific experiment will be taken during spring 2002.

2.6 Microbe Project

Background

A set of microbiology research tasks for the performance assessment of high level radioactive waste disposal has been identified /Pedersen, 1999/. Those with a potential for study at the MICROBE site deal with redox stability of the host rock environment, radionuclide transport and copper corrosion. Microbes produce and consume gases. It is important to understand to what extent microbial production and consumption of gases like carbon dioxide, hydrogen, nitrogen and methane will influence the performance of a repository. Microbes are supposed to have an influence on radionuclide migration. The extent of microbial dissolution of immobilised radionuclides and production of complexing agents that increase radionuclide migration rates should be studied. Attached microbes on fracture walls and fillings may retard migrating radionuclides and this process should be evaluated as it may add as a retention component in transport models. Bio-corrosion of the copper canisters, if any, will be a result of microbial sulphide production. Survival and activity of sulphide-producing bacteria in the bentonite buffer would result in production of sulphide in the bentonite surrounding the canisters. The present hypothesis is that highly compacted bentonite does not allow microbial sulphide producing activity. This hypothesis needs testing under relevant repository conditions. The Microbe Project will according to present plans continue until 2006.

Objectives

The major objectives for the Microbe Project are:

- To assay microbial activity in groundwater at in-situ conditions. The microbial influence on redox conditions, radionuclide migration and gas production and consumption will be in focus.
- To establish data on hydrogen generation and flow in granitic rock environments. The flow of hydrogen from where it is produced will determine the possible rate of long-term microbial redox stabilising activity, especially during periods of glaciation.
- To enable experiments where engineered barriers (e.g. bentonite, backfill and copper) can be investigated for the influence of micro-organisms at realistic and controlled conditions with a significant knowledge about groundwater used.
- To generate accurate data about rates of microbial reactions at repository conditions, for performance assessment calculations.

These objectives have been addressed in a range of projects, of which some are ongoing. Important conclusions have been obtained based on laboratory and field data. While some results seem very solid with general applicability, others are pending inspection at in-situ conditions. This is especially true for data generated at the laboratory only. In-situ generated data must be obtained for microbial activities anticipated in the far- and near-field environment at realistic repository conditions. This can be achieved at an underground site, developed for microbiological research, using circumstantial protocols for contamination control during drilling and operation.

Experimental concept

Three Microbe sites have been opened in Äspö HRL. The main site is at the 450 m level and consists of three core drilled boreholes (KJ0050F01, KJ0052F01 and KJ0052F03) intersecting water conducting fractures at 12.7, 43.5 and 9.3 ms depth respectively. Each borehole is equipped with metal free packer systems that allow controlled sampling of respective fracture. An underground laboratory is installed close to the boreholes, which is equipped with a large anaerobic chamber and basic laboratory equipment. Tubings connect the boreholes with the laboratory. This site will be used to investigate how the micro-organisms on the fracture surfaces may influence the radionuclide transport.

Two additional Microbe experimental sites have been opened in the Äspö tunnel. A side vault (at tunnel length 1127B) has a constructed, shallow pond (2000 x 1000 x 10 cm) with an unique populations of sulphur oxidising bacteria. This site will be used for investigations of microbial stable isotope fractionation of sulphur in sulphate, sulphur and sulphide.

The other site (2200A m), at 296 m depth is equipped with open flow channels feed with groundwater from a packed off borehole. The borehole has earlier been used for rock tension measurements (BSP 2200). Trace element retention by the biological iron oxide systems (BIOS) will be studied. BIOS are commonly forming when ferrous iron containing groundwater comes under oxidising conditions, such as outflow into an oxygenic atmosphere. Earlier results indicated a significant metal retention effect from the biological part of naturally occurring iron oxides.

The site is also used for a continuation of buffer tests including a study of the potential for microbial copper corrosion at repository conditions

Present status

The packers and the circulation system as well as the container have been installed on the 450 m level. Biofilms (bio-mobilisation) have build up in borehole KJ0052F03, which has been investigated. The work with the installation of temperature controlled circulation systems at the 450 m site is ongoing.

The vault roof has been secured in the 2200 vault and the BSP-borehole has been equipped with packers.

Flow through tanks (2000 x 300 x 200 cm) has been installed and equipped width gravel and artificial supports for BIOS attachment and growth on the 2200 BIOS site.

A first experiment concerning microbial corrosion of copper has been run and evaluated during 2001.

Scope of work for 2002

The planned work for 2002 mainly comprise the following.

- Constructed surfaces with defined concentrations of trace elements will be exposed to microbial bio-films at the 450 m site after summer 2002, when the circulation systems are running.
- The flow through tanks will be run and oxygen and pH profiles will be shed and measured. Trace element analysis and groundwater chemical composition will be analysed. Retention of naturally occurring trace elements on the BIOS will be investigated.
- A second round of bentonite incubations (microbial corrosion of copper) will preliminary start summer 2002. Details will be planned after final evaluation of the 2001 experiments, end of spring 2002.

Work is ongoing at the 450 m site with the experiment for the microbial effects on the chemical stability. The systems will allow experiments under in-situ pressure, gas composition and in-situ chemical conditions. The experiments are planned to be up and running after summer 2002. Field gas chromatograph and gas extraction systems are being developed during spring 2002 for measurements of dissolved hydrogen and methane in groundwater. Bio-film experiments will start after summer 2002. The bio-films will be used for trace element immobilisation, mobilisation experiments, and for investigations of microbial influences on the chemical and redox stability in deep ground water.

2.7 Matrix Fluid Chemistry

Background

Knowledge of matrix fluids and groundwaters from crystalline rocks of low hydraulic conductivity ($K < 10^{-10}$ ms^{-1}) will complement the hydrogeochemical studies already conducted at Äspö, for example, matrix fluids are suspected to contribute significantly to the salinity of deep formation groundwaters. Small-scale fractures and fissures will facilitate migration of matrix fluids. Therefore the matrix fluid chemistry will be related to the chemistry of groundwaters present in hydraulically conducting minor fractures ($K = 10^{-10}$–10^{-9} ms^{-1}). This is important to repository performance since it will be these groundwaters that may initially saturate the bentonite buffer material in the deposition holes. Such data will provide a more realistic chemical input to near-field performance and safety assessment calculations.

Objectives

The main objectives of the Matrix Fluid Chemistry experiments are to:

- Determine the origin and age of the matrix fluids.
- Establish whether present or past in- or out-diffusion processes have influenced the composition of the matrix fluids, either by dilution or increased concentration.
- Derive a range of groundwater compositions as suitable input for near-field model calculations.
- Establish the influence of fissures and small-scale fractures (when present) on fluid chemistry in the bedrock.

Experimental concept

The Matrix Fluid Chemistry experiments comprise:

- Feasibility study carried out on drill core material. The mineralogy and major tracer element geochemisty is investigated to generally characterise the rock mass.
- Leaching and permeability experiments including cruch/leach experiments to indicate the nature of the matrix fluid.
- Full scale program comprising (a) mineralogical and petrophysical studies, (b) porosity measurements, (c) crush/leaching experiments, (d) Äspö diorite permeability test, (e) fluid inclusion studies, (f) matrix fluid sampling, and (g) compilation and interpretation of groundwater and hydraulic data from the TRUE, Prototype Repository, CHEMLAB and Microbe experiments, representing the bedrock environment in the near-vicinity of the Matrix Fluid Chemistry borehole.

The experiment in the full-scale programme is designed to sample matrix fluids from predetermined, isolated borehole sections. The borehole was selected on the basis of: (a) rock type, (b) mineral and geochemical homogeneity, (c) major rock foliation, (d) depth in the tunnel, (e) presence and absence of fractures, and (f) existing groundwater data from other completed and on-going experiments at Äspö HRL.

Special equipment, see Figure 2-9, has been designed to sample the matrix fluids ensuring: (a) an anaerobic environment, (b) minimal contamination from the installation, (c) minimal dead space in the sample section, (d) the possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock, (e) in-line monitoring of electrical conductivity and drilling water content, (f) the collection of fluids (and gases) under pressure, and (g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

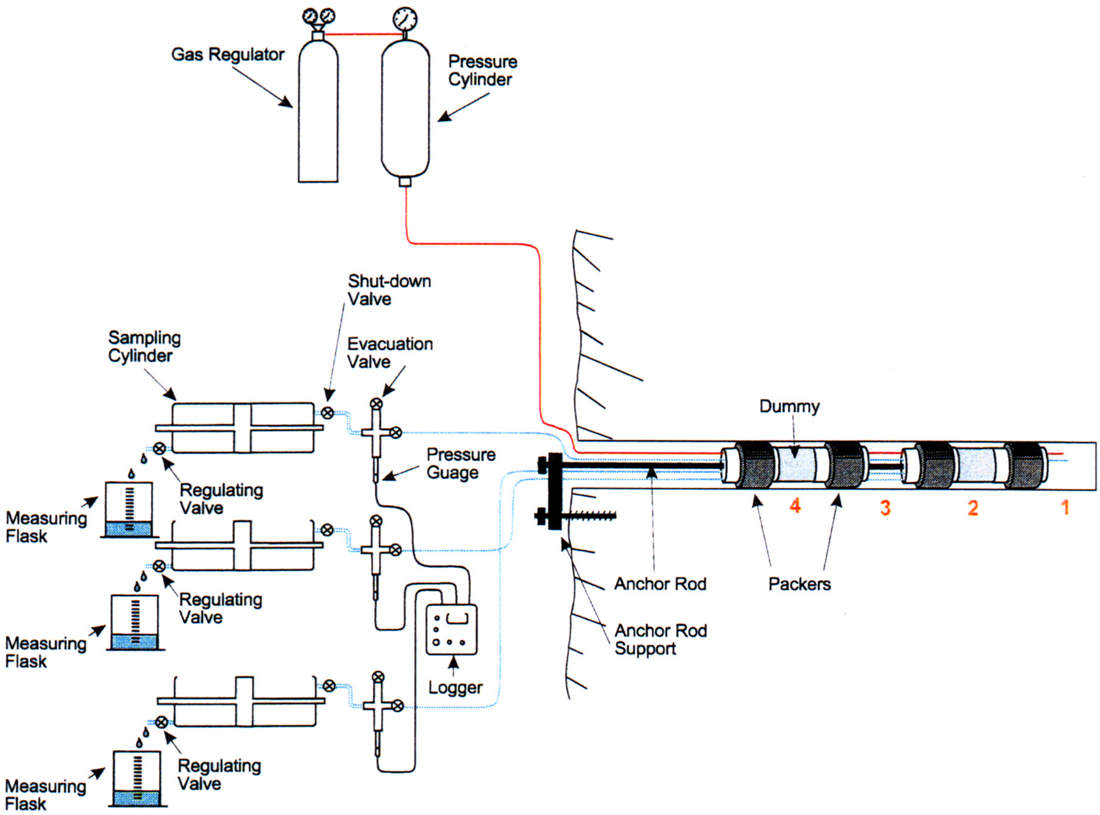

Figure 2-9. Matrix Fluid Chemistry experimental set-up. Borehole sections 2 and 4 were selected to collect matrix fluid; sections 1-4 are continuously monitored for pressure.

Present status

The Matrix Fluid Chemistry project was initiated in June 1998 and most of the gathering of scientific data was conducted and reported by December 2001, which marked the official completion of the project.

The completion of two studies, however, was still outstanding: (a) matrix fluid leaching of drill core material using distilled water under inert laboratory conditions (University of Bern), and (b) a high-pressure permeability experiment to try and force matrix fluid from an intact drill core section (University of Waterloo). For experiment (a) this was continued into 2002 to ensure more relevant data, and experiment (b) was continued in the hope that some matrix fluid could be extracted prior to final reporting.

Most of the completed studies have been documented as ITD Reports; the halfway progress of the project was reported in detail in 2000 /Smellie, 2000/.

Scope of work for 2002

Scope of work for 2002 will be to conclude the two outstanding experiments mentioned above in May and to complete reporting of the total project by the summer.

2.8 Modelling of groundwater flow and transport of solutes

An overall objective of the defined experiment is to increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock and to increase the credibility in the computer models used for radionuclide transport and groundwater flow.

A Task Force on Modelling of Groundwater Flow and Transport of Solutes has been created at the Äspö HRL to serve as a forum for consultation and discussion of conceptual and numerical modelling of groundwater flow and radionuclide transport.

Numerical modelling of groundwater flow, the NUMMOD Project, involves continued development of the numerical calculation models to be used in the evaluation of site characterisation and performance assessment. The project is connected to the Äspö Task Force on Groundwater Flow and Transport of Solutes.

2.8.1 The Task Force on Modelling of Groundwater Flow and Transport of Solutes

Background

The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes was initiated in 1992. The group consists of eight organisations from seven countries. A Task Force delegate represents each participating organisation and the modelling work is performed by modelling groups. The Task Force meets regularly about once to twice a year. Different experiments at the Äspö HRL are utilised to support the Modelling Tasks. To date modelling issues and their status are as follow:

Task 1: Long-term pumping and tracer experiments (LPT-2). Completed.

Task 2: Scooping calculations for some of the planned detailed scale experiments at the Äspö site. Completed.

Task 3: The hydraulic impact of the Äspö tunnel excavation. Completed.

Task 4: The Tracer Retention and Understanding Experiment (TRUE), 1st stage. On-going.

Task 5: Coupling between hydrochemistry and hydrogeology. On-going.

Task 6: Performance Assessment (PA) Modelling Using Site Characterisation (SC) Data (PASC). On-going.

Objectives

The Äspö Task Force is a forum for the organisations supporting the Äspö Hard Rock Laboratory Project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate and contribute to such work in the project. The Task Force shall interact with the principal investigators responsible for carrying out experimental and modelling work for Äspö HRL of particular interest for the members of the Task Force.

Much emphasis is put on building of confidence in the approaches and methods in use for modelling of groundwater flow and migration in order to demonstrate their use for performance and safety assessment.

Scope of work for 2002

The main objectives targeted to be accomplished during 2002 are summarised below:

- Complete the overall evaluation of the modelling conducted in Task 4 and publish a report.
- Publish all Task 5 modelling reports.

– Complete and publish the Task 5 Summary report.

– Complete and publish the Task 5 Reviewers report.

– Organise a workshop on Task 5.

– Produce the final modelling report for Task 6A (modelling selected tracers used within TRUE-1) and 6B (modelling selected tracers used within the TRUE-1 program with new performance assessment relevant boundary conditions and time scales).

– Organise a workshop on Task 6C - the structural model.

– Delivery of Task 6C structural model to modelling groups.

– Organise the 16th International Task Force meeting, hosted by SKB at Äspö.

2.8.2 Numerical Modelling of Groundwater Flow (NUMMOD)

Background

Mathematical models for groundwater flow and transport are important tools in the characterisation and assessment of underground waste disposal sites. SKB has during the years developed and tested a number of modelling tools. Numerical models for groundwater flow and transport have been developed and used at Äspö HRL in regional and site scale /Svensson, 1997a,b/ as well as in the laboratory scale /Svensson, 1999a/. Several modelling concepts such as Stochastic Continuum (SC) and Discrete Fracture Network (DFN) concepts have been used. The results from the modelling work show that there is a need to develop the numerical models.

The development comprises e.g. the methodology where a fracture network is used for assigning hydraulic properties to a SC model. The methodology of how to transform the fracture network to a SC was shown in /Svensson, 1999b/.

Based on the new data available since the Äspö model 1996, reported in Rhén et al. /1997/, and the new concept of generating the conductivity field /Svensson, 1999b/, it is planned to update the site, laboratory and regional models of the Äspö area. However, some of this updating will be performed within the context of the Task Force. Furthermore, the code DarcyTools will be used as a modelling tool within the site characterisation programme.

Objectives

The general objective is to improve the numerical model in terms of flow and transport and to update the site scale and laboratory scale models for the Äspö HRL. The models should cover scales from 1 to 10 000 m and be developed for the Äspö site, but be generally applicable.

The specific objectives with the updated models are:

– Test and improve new methodology of generating a conductivity field based on a fracture network in a continuum modelling approach.

– Develop models for transport and dispersion.

– Improve the methodology for calibration and conditioning the model to observed conductive features of the groundwater flow models.

– Improve the handling of the inner boundary conditions in terms of generating the tunnel system and applying boundary conditions.

– Improve the data handling in terms of importing geometrical data from the Rock Visualization System (RVS) to the numerical code for groundwater flow and to export modelling results to RVS.

– Increase the details in the models based on new knowledge of the Äspö site collected during the last years.

Modelling concept

The modelling of groundwater flow and transport in sparsely fractured rock is made with three different concepts: Stochastic Continuum (SC), Discrete Fracture Network (DFN) and Channel Network (CN). The last modelling approach has similarities with the SC approach. Experiences gained from international modelling tasks within the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes have shown that the different concepts are all useful but there are needs to develop the codes both in terms of data handling and visualisation. It is also necessary to continue developing and testing the concepts /Gustafson and Ström, 1995; Gustafson et al., 1997/. The model code used is DarcyTools (previously called PHOENICS when a different solver was used), which has been used in regional scale, site scale and laboratory scale models /Svensson 1997a,b; 1999a/.

Scope of work for 2002

The main tasks are:

– *Reporting of Part 1 of NUMMOD in two reports;* DarcyTools – Concepts, method, equations and tests, DarcyTools – Software description and documentation. The second report may later on be developed into a full User's Guide.

– *Launching of versions 1.0 and 2.0 of DarcyTools.* DarcyTools version 1.0 will be launched during the first quarter of 2002. During the remaining part of 2002, version 1.0 will be tested and evaluated so that an official version 2.0 can be launched by the end of the year.

– *Execution of Part 2 of NUMMOD.* The second part of NUMMOD consists of several activities to be performed prior to launching of DarcyTools version 2.0; project-external assessment/review of version 1.0, possible optimisation of the code, confidence building, and application of version 1.0. Finally, modifications in code routines (primarily RVS interface, user-friendly input/output interfaces, and QA-routines) may be performed.

– *Participation in Task 6 of the Äspö Task Force.* The scope of Task 6 is to model flow and radionuclide transport in a single fracture and in a fracture network (block scale) for typical field scale experimental conditions and for conditions relevant for performance assessment. The objective is to evaluate how models perform when applied on different temporal and spatial scales. This exercise will substitute the previously planned update of the Äspö model on the laboratory scale.

– *Use of DarcyTools in site characterisation programme.* During 2002 a regional model of the Oskarshamn region will be initiated. DarcyTools version 1.0 will be used in the start of the project; however, all final results will be produced with DarcyTools version 2.0. The modelling activities within the site characterisation programme are performed outside the scope of the NUMMOD project.

3 Demonstration of technology for and function of important parts of the repository system

3.1 General

One of the goals for Äspö HRL is to demonstrate technology for and function of important parts of the repository system. This implies translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in a real repository.

It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, are conducted under realistic conditions and at appropriate scale. A number of large-scale field experiments and supporting activities are therefore conducted at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing, and will together form a major experimental program.

With respect to *technology demonstration* important overall objectives of this program are:

- To furnish methods, equipment and procedures required for excavation of tunnels and deposition holes, near-field characterisation, canister handling and deposition, backfill, sealing, plugging, monitoring and also canister retrieval.
- To integrate these methods and procedures into a disposal sequence, that can be demonstrated to meet requirements of quality in relation to relevant standards, as well as practicality.

With respect to *repository function*, the objectives are:

- To test and demonstrate the function of components of the repository system.
- To test and demonstrate the function of the integrated repository system.

The main experiments that are installed or under way are:

- Prototype Repository.
- Backfill and Plug Test.
- Canister Retrieval Test (CRT).
- Long Term Test of Buffer Material (LOT).
- Pillar Stability Experiment.

3.2 Demonstration of repository technology

The design, manufacturing and testing of the equipment for handling and deposition of the buffer material and canisters for the CRT and the Prototype Repository was completed during 2000. The equipment, mainly a mobile gantry crane and a small canister deposition machine, was used for the installation of buffer material and canister with heaters for the CRT. After some modification the same equipment is used for the deposition of buffer material and canisters in the Prototype Repository.

The engineering experiments at Äspö HRL, except for the Prototype Repository, are now implemented and are in the operational phase for data collection. This is valid for the Backfill and Plug Test, Canister Retrieval Test, Long Term Testing of Buffer Material. Regarding the Prototype Repository, the inner section with four canisters was installed at the end of 2001. The remaining two canisters, will be installed in the outer section early 2002 and that part of the tunnel will be backfilled and sealed with a concrete plug mid 2002.

The development work of the equipment needed in the future deep repository will continue during 2002 and onwards based on experiences from the work with the demonstration deposition machine installed at Äspö HRL. The whole system of different machines and equipment needed is expected to be identified and developed to a feasibility stage as part of the ongoing design studies of the deep repository.

3.3 Prototype Repository

Background

Many aspects of the KBS-3 repository concept have been tested in a number of in-situ and laboratory tests. Models have been developed that are able to describe and predict the behaviour of both individual components of the repository, and the entire system. However, processes have not been studied in the complete sequence, as they will occur in connection to repository construction and operation. There is a need to test and demonstrate the execution and function of the deposition sequence with state-of-the-art technology in full-scale. In addition, it is needed to demonstrate that it is possible to understand and qualify the processes that take place in the engineered barriers and the surrounding host rock. It is envisaged that this technology can be tested, developed and demonstrated in the Prototype Repository.

The execution of the Prototype Repository is a dress rehearsal of the actions needed to construct a deep repository from detailed characterisation to resaturation of deposition holes and backfill of tunnels. The Prototype Repository will provide a demonstration of the integrated function of the repository and provide a full-scale reference for test of predictive models concerning individual components as well as the complete repository system. The Prototype Repository should demonstrate that the important processes that take place in the engineered barriers and the host rock are sufficiently well understood.

The Prototype Repository is co-funded by the European Commission for a 42 months period starting September 2000 with SKB as Co-ordinator and including seven participating organisations, see Section 5.3.

Objectives

The main objectives for the Prototype Repository are:

- To test and demonstrate the integrated function of the deep repository components under realistic conditions in full-scale and to compare results with models and assumptions.
- To develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- To simulate appropriate parts of the repository design and construction processes.

The evolution of the Prototype Repository should be followed for a long-time, possible up to 20 years. This is made to provide long-term experience on repository performance to be used in the evaluation that will be made after the initial operational stage in the real deep repository.

Experimental concept

The Prototype Repository should, to the extent possible, simulate the real deep repository system, regarding geometry, materials, and rock environment. This calls for testing in full-scale and at relevant depth.

The test location chosen is the innermost section of the TBM tunnel at 450 m depth. The layout involves altogether six deposition holes, four in an inner section and two in an outer, see Figure 3-1. The tunnels will be backfilled with a mixture of bentonite and crushed rock (30/70). A massive concrete plug designed to withstand full water and swelling pressures will separate the test area from the open tunnel system and a second plug will separate the two sections. This layout will in practice provide two more or less independent test sections. Canisters with dimension and weight according to the current plans for the deep repository and with heaters to simulate the thermal energy output from the waste will be positioned in the holes and surrounded by bentonite buffer. The deposition holes are with a centre distance of 6 m. This distance is evaluated considering the thermal diffusivity of the rock mass and the fact that maximum acceptable surface temperature of the canister is 90°C.

The test arrangement should be such that artificial disturbance of boundary conditions or processes governing the behaviour of the engineered barriers and the interaction with the surrounding rock are kept to a minimum.

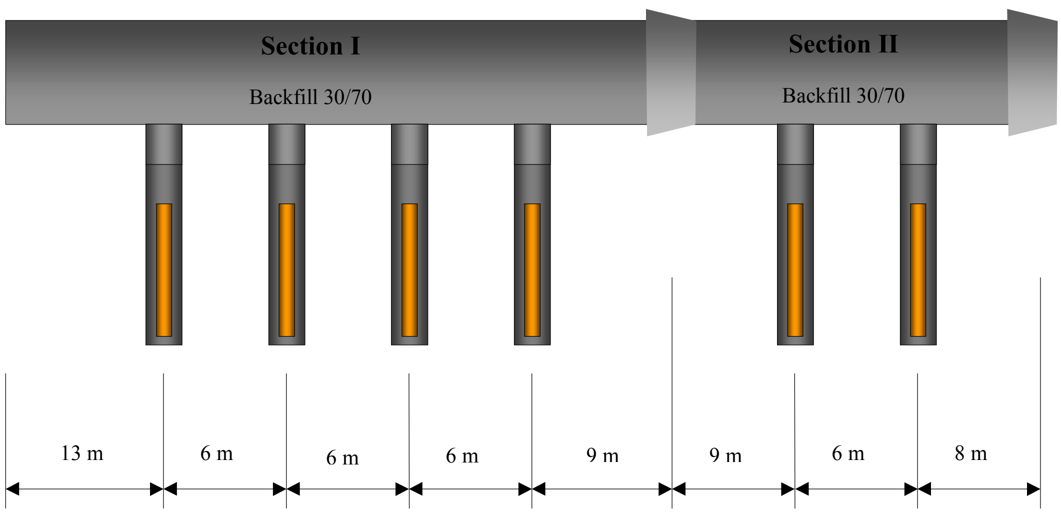

Figure 3-1. *Schematic view of the layout of the Prototype Repository. (not to scale)*

Operation time for the experiment is envisaged to be at least 10 years, possible up to 20 years. Decision as to when to stop and decommission the test will be influenced by several factors, including performance of monitoring instrumentation, results successively gained, and also the overall progress of the deep repository project. It is envisaged that the outer test section will be decommissioned after approximately five years to obtain interim data on buffer and backfill performance through sampling.

Instrumentation will be used to monitor processes and properties in the canister, buffer material, backfill and the near-field rock. The intention to minimise disturbance will, however, add restrictions to the monitoring possible.

Processes that will be studied include:

- Water uptake in buffer and backfill.
- Temperature distribution in canisters, buffer, backfill and rock.
- Displacements of canisters.
- Swelling pressure and displacement in buffer and backfill.
- Stresses and displacements in the near-field rock.
- Water pressure build up and pressure distribution in rock.
- Gas pressure in buffer and backfill.
- Chemical processes in rock, buffer and backfill.
- Bacterial growth and migration in buffer and backfill.

Present status

The canisters, buffer and backfill in the inner section were installed during 2001 and the plug between the inner and outer section was cast at the end of 2001. Monitoring of processes and properties in the canisters, buffer material, backfill and in the near-field rock are ongoing.

The rock work including boring and lining of lead-troughs to the adjacent tunnel for cables and tubes for all instruments, gas and water sampling units and heaters in the canisters were finalised in the outer section during winter 2001.

Scope of work for 2002

The major topics during 2002 are the installation of the remaining two canisters in the outer section including backfill and casting of the end plug that separates the test area from the rest of Äspö HRL.

The installation in the outer section comprises instruments in the rock surrounding the deposition holes, canisters with heaters, buffer as well as instruments in the deposition hole. All preparations including installation of cable packages will almost be completed during the first quarter of 2002. The deposition of the canisters and bentonite blocks and casting of the plug were originally planned during 2002. The recently indicated malfunction of the heaters in the Canister Retrieval Test is presently judged to have an influence also on the Prototype Repository project as all heaters are of the same design. This would suggest a first phase of determining the cause and a second phase of adjusting the design before continuing the installation.

Monitoring and data collection of the inner section is continued and initiated in the outer section. The monitoring and data collection will continue until 2007 in the outer section and until 2020 in the inner section.

3.4 Backfill and Plug Test

Background

The Backfill and Plug Test is a test of different backfill materials and emplacement methods and a test of a full-scale plug. It is a test of the hydraulic and mechanical function of the backfill materials and their interaction with the near-field rock. It is also a test of the hydraulic and mechanical function of a plug. The test is partly a preparation for the Prototype Repository.

Objectives

The main objectives of the Backfill and Plug Test are:

- To develop and test different materials and compaction techniques for backfilling of tunnels excavated by blasting.
- To test the function of the backfill and its interaction with the surrounding rock in full-scale in a tunnel excavated by blasting.
- To develop technique for building tunnel plugs and to test the function.

Experimental concept

The test region for the Backfill and Plug Test is located in the old part of the ZEDEX drift. Figure 3-2 shows a 3D visualisation of the experimental set-up. The test region can be divided into the following three test parts:

- The inner part filled with a mixture of bentonite and crushed rock (six sections).
- The outer part filled with crushed rock and bentonite blocks and pellets at the roof (four sections).
- The plug.

The backfill sections were applied layer wise and compacted with vibrating plates that were developed and built for this purpose. It was concluded from preparatory tests that inclined compaction should be used in the entire cross section from the floor to the roof and that the inclination should be about 35 degrees.

The inner test part was filled with a mixture of bentonite and crushed rock with a bentonite content of 30%. The composition is based on results from laboratory tests and field compaction tests. The outer part was filled with crushed rock with no bentonite additive. A slot of a few dm was left between the backfill and the roof. The slot was filled with a row of highly compacted blocks with 100% bentonite content, in order to ensure a good contact between the backfill and the rock, since the crushed rock has no swelling potential and may instead settle with time. The remaining irregularities between these blocks and the roof were filled with bentonite pellets.

The test region is about 28 m long and it is divided into sections by drainage layers of permeable mats in order to apply hydraulic gradients between the layers and to study the flow of water in the backfill and the near-field rock. The mats are also used for the water saturation of the backfill.

The backfill and rock were instrumented with piezometers, total pressure cells, thermocouples, moisture gauges, and gauges for measuring the local hydraulic conductivity. The axial conductivity of the backfill and the near-field rock will after water saturation be tested by applying a water pressure gradient along the tunnel between the mats and measuring the water flow. All cables from the instruments were enclosed in Tecalan tubes in order to prevent leakage through the cables. The cables were led through the rock to the data collection room in boreholes drilled between the test tunnel and the neighbouring Demo-tunnel.

The plug is designed to resist water and swelling pressures that can be developed. It is equipped with a filter on the inside and a 1.5 m deep triangular slot with an "O-ring" of highly compacted bentonite blocks at the inner rock contact, see Figure 3-2.

The flow testing in the backfill is planned to start after saturation, when steady state flow and pressure have been reached.

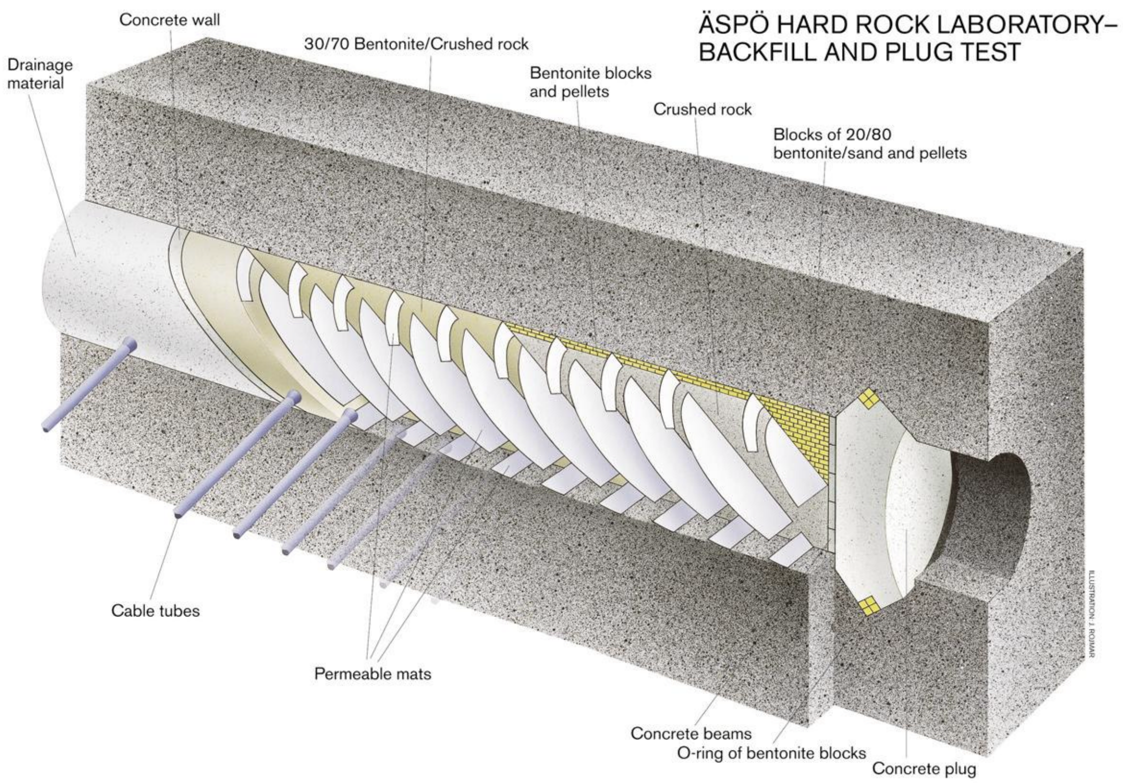

Figure 3-2. Illustration of the experimental set-up of the Backfill and Plug Test.

Present status

The entire test set-up with backfill, instrumentation and building of the plug was finished in the end of September 1999 and the wetting of the 30/70 mixture through the filter mats started in late November 1999. Wetting of the backfill from the filter mats and the rock has continued during the years 2000 and 2001 and data from transducers has been collected and reported. In order to increase the rate of water saturation the water pressure in the mats was increased to 400 kPa in the autumn 2001. At the end of 2001 complete water saturation has reached about 20 cm into the 30/70 backfill, while in average the degree of saturation in the centre of the sections have increased to about 70%.

Scope of work for 2002

The following main activities are planned:

- Continued wetting of the backfill with increased water pressure in the mats. The water pressure will be increased to 500 kPa in January and kept at 500 kPa until May, when an evaluation of the effect will settle whether to increase it further or keep it at 500 kPa during the rest of the year.
- Continued data collection and reporting of measured water pressure, water flow, total pressure and degree of water saturation.
- Maintenance of equipment and supervision of the test.
- Supplementary laboratory tests in order to increase the understanding and further develop the models of water unsaturated backfill.
- Supplementary modelling of the water saturation phase and evaluation of results.

If the wetting rate agrees with the predictions, the backfill should be water saturated and the flow testing can start during 2003.

3.5 Canister Retrieval Test

Background

The stepwise approach to safe deep disposal of spent nuclear fuel implies that if the evaluation of the deposition after the initial stage is not judged to give a satisfactory result the canisters may need to be retrieved and handled in another way. The evaluation can very well take place so long after deposition that the bentonite has swollen and applies a firm grip around the canister. The canister, however, is not designed with a mechanical strength that allows the canister to be just pulled out of the deposition hole. First the canister has to be made free from the grip of the bentonite before the canister can be taken up into the tunnel and enclosed in a radiation shielding before being transported away from the deposition area.

The Canister Retrieval Test is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite is fully saturated and has its maximum swelling pressure. The process covers the retrieval up to the point when the canister is safely emplaced in a radiation shield and ready for transport to the ground surface.

Objectives

The overall aim of the Canister Retrieval Test is to demonstrate to specialists and to the public that retrieval of canisters is technically feasible during any phase of operation, especially after the initial operation. The following was defined to fulfil the aim of the canister retrieval test:

- Two vertically bored test holes in full repository scale, which fulfil the quality requirements deemed necessary for the real repository.
- Careful and documented characterisation of the properties of these holes including the boring disturbed zone.

– Emplacement of bentonite blocks, bentonite pellets and canisters with heaters, and artificial addition of water in accordance to conditions planned for the real repository. However, for different reasons only one of these deposition holes has been used for implementation of the Canister Retrieval Test.

– Saturation and swelling of the buffer under controlled conditions, which are monitored.

– Preparations for testing of canister retrieval.

Boring of full-scale deposition holes and geometrical/geotechnical characterisation of holes as well as emplacement of bentonite and canister with heaters are made within sub-projects that concern also other tests in the Äspö HRL.

Experimental concept

The Canister Retrieval Test is located in the main test area at the 420 m level, and is separated into three stages:

Stage I: Boring of deposition holes and installation of bentonite blocks and canisters with heaters. The holes are covered in the top with a lid of concrete and steel.

Stage II: Saturation of the bentonite and evolution of the thermal regime.

Stage III: Test of freeing the canister from the bentonite, docking the gripping device to the canister lid and lifting of the canister up to the tunnel floor and into the radiation shield on the deposition machine (reversed deposition sequence).

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with a full diameter of 1.65 m and a nominal height of 0.5 m. When the stack of blocks was 6 m high the canister equipped with electrical heaters was lowered down in the centre. Cables to heaters, thermocouples and strain gauges are connected, and further blocks are emplaced until the hole was filled up to 1 m from the tunnel floor. On top the hole was sealed with a plug made of concrete and a steel plate as cover. The plug was secured against heave caused by the swelling clay with cable anchored to the rock. The tunnel will be left open for access and inspections of the plug support, see Figure 3-3.

Artificial addition of water is provided regularly around the bentonite blocks by means of permeable mats attached to the rock wall. The design of the mats was done so that they are not disturbing the future test of retrieval.

Predicted saturation time for the test is about two-three years in the 350 mm thick buffer along the canister and about 5 years in the buffer below and above the canister. Decision on when to start the retrieval tests is dependent on information of the degree of saturation, and instruments will be installed to monitor the process in different parts of the buffer. This instrumentation is similar to the instrumentation in the Prototype Repository and yield comparable information during the saturation period. The intention to minimise disturbance during retrieval tests, however, restricts the number and locations of instruments.

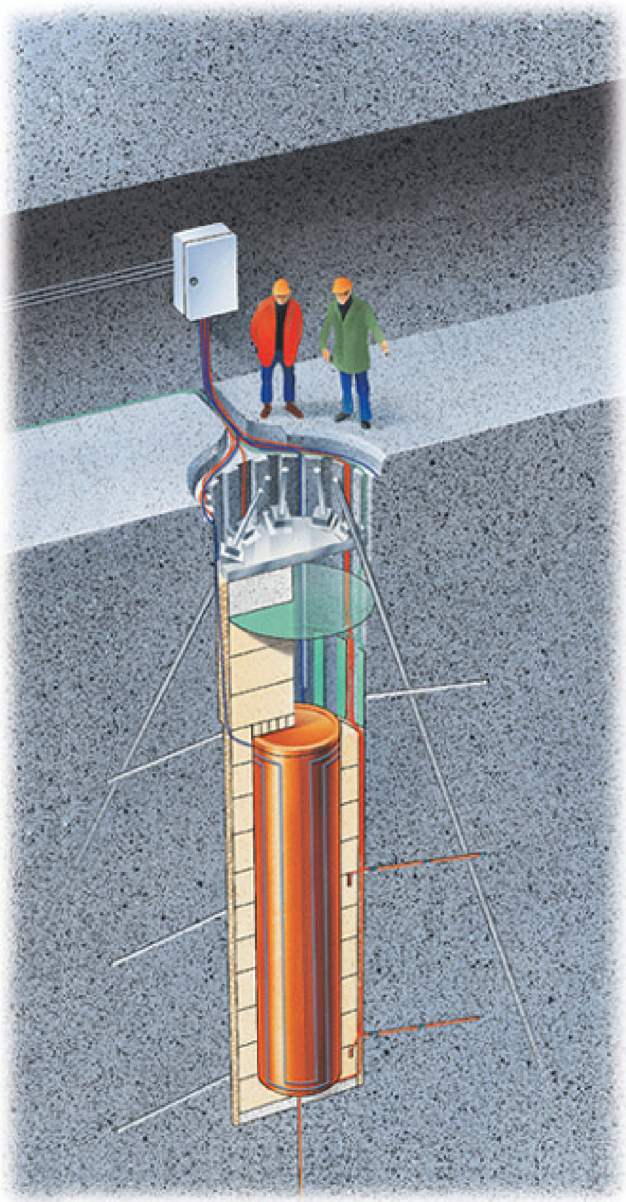

Figure 3-3. *Experimental set-up in Canister Retrieval Test.*

Present status

Two holes were bored but only one has been installed, the reason being that only one robust method for freeing the canister is presently considered to be tested in full-scale in the Äspö HRL.

The installation of the buffer material and the canister with instrumentation and heaters started mid September 2000 and was completed during October 2000 including the in-situ casting of the concrete plug on top of the bentonite buffer. The heaters were turned on and the artificial watering of the buffer material started in October 2000, and the operation of the Canister Retrieval Test is planned to continue for some 4 to 5 years, until the bentonite buffer has been fully saturated.

The artificial water supply to the surrounding permeable mats has continued and the water flow is registered. Registration of sensor readings, concerning temperature, water content, rock stresses etc., is continued. Data measured during the period October 2000 to October 2001 have been compiled and are published in a data report /Goudarzi et al., 2001/.

One major drawback came in November, 2001 when a fuse broke indicating a short-circuit in the heater's electrical system. The investigation revealed that 2 of the 36 heater elements had direct contact with earth. After measurements revealing the problem it was decided that the earlier operating heaters plus two new ones should be turned on in order to provide the needed experimental conditions until an alternative plan of retrieval had been developed in case all heaters would be short-circuited. So far, February 2002, the heating has continued without problem.

Scope of work for 2002

The plan is to continue the artificial water saturation of the bentonite and to continue the registration of sensor readings.

If all heaters fail the original plan was to lift up the steel and concrete plug in the top of the hole and to excavate the bentonite buffer with continuos sampling. When the canister lid has been made free it is possible to determine whether the problem is inside the canister or outside. If the verdict is "inside" the canister has to be retrieved, while more samples from the bentonite buffer can be extracted, with major benefit for the modellers. If the verdict is "outside" the aim is to repair the failure and re-build the test with new bentonite blocks for continuing the saturation of the buffer.

The earlier plan to interrupt the test to find the cause of the short-circuit problems and to see what parts have been affected has, however, been revised. A task force has been appointed to investigate, evaluate and to establish correcting or preventing measures. Continuous readings of resistance versus temperature and time have been performed on site and also under controlled conditions in a full-scale, workshop test. Tests on materials involved in the canister/heater system are also performed to find or exclude possible explanations to the problem. As a consequence of this work it was judged that the Canister Retrieval Test could be in operation until further notice. The time factor is considered vital to give comparable results for the full-scale test in relation to the measured development on site. Therefore, it was deemed necessary to postpone the final decision regarding investigation on site and also correcting or preventing measures till after the summer.

3.6 Long Term Test of Buffer Material

Background

Bentonite clay has been proposed as buffer material in several concepts for HLW repositories. In the Swedish KBS-3 concept the demands on the bentonite buffer are to serve as a mechanical support for the canister, reduce the effects on the canister of a possible rock displacement, and minimise water flow over the deposition holes.

The decaying power from the spent fuel in the HLW canisters will give rise to a thermal gradient over the bentonite buffer by which original water will be redistributed parallel to an uptake of water from the surrounding rock. A number of laboratory test series, made by different research groups, have resulted in various buffer alterations models. According to these models no significant alteration of the buffer is expected to take place at the prevailing physico-chemical conditions in a KBS-3 repository neither during nor after water saturation. The models may to a certain degree be validated in long-term field tests. Former large scale field tests in Sweden, Canada, Switzerland and Japan have in some respects deviated from possible KBS-3 repository conditions and the testing periods have generally been dominated by initial processes, i.e. water uptake and temperature increase.

Objectives

The present test series aims at validating models and hypotheses concerning physical properties in a bentonite buffer material and of related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport under conditions similar to those in a KBS-3 repository. The expression "long-term" refers to a time span long enough to study the buffer performance at full water saturation, but obviously not "long-term" compared to the lifetime of a repository. The objectives may be summarised in the following items:

– Data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, cation exchange capacity and hydraulic conductivity.

– Check of existing models on buffer-degrading processes, e.g. illitization and salt enrichment.

– Information concerning survival, activity and migration of bacteria in the buffer.

– Check of calculation data concerning copper corrosion, and information regarding type of corrosion.

– Data concerning gas penetration pressure and gas transport capacity.

– Information, which may facilitate the realisation of the full-scale, test series with respect to clay preparation, instrumentation, data handling and evaluation.

Experimental concept

The testing principle for all planned tests is to emplace "parcels" containing heater, central tube, pre-compacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m, see Figure 3-4. The test series, given in Table 3-1, concern realistic repository conditions except for the scale and the controlled adverse conditions in three tests.

Table 3-1 Lay out of buffer material test series.

Type	No.	max T, °C	Controlled parameter	Time, years	Remark
A	1	130	T, [K^+], pH, am	1	pilot test
A	0	120–150	T, [K^+], pH, am	1	main test
A	2	120–150	T, [K^+], pH, am	5	main test
A	3	120–150	T	5	main test
S	1	90	T	1	pilot test
S	2	90	T	5	main test
S	3	90	T	>>5	main test

A = adverse conditions S = standard conditions
T = temperature [K^+] = potassium concentration
pH = high pH from cement am = accessory minerals added

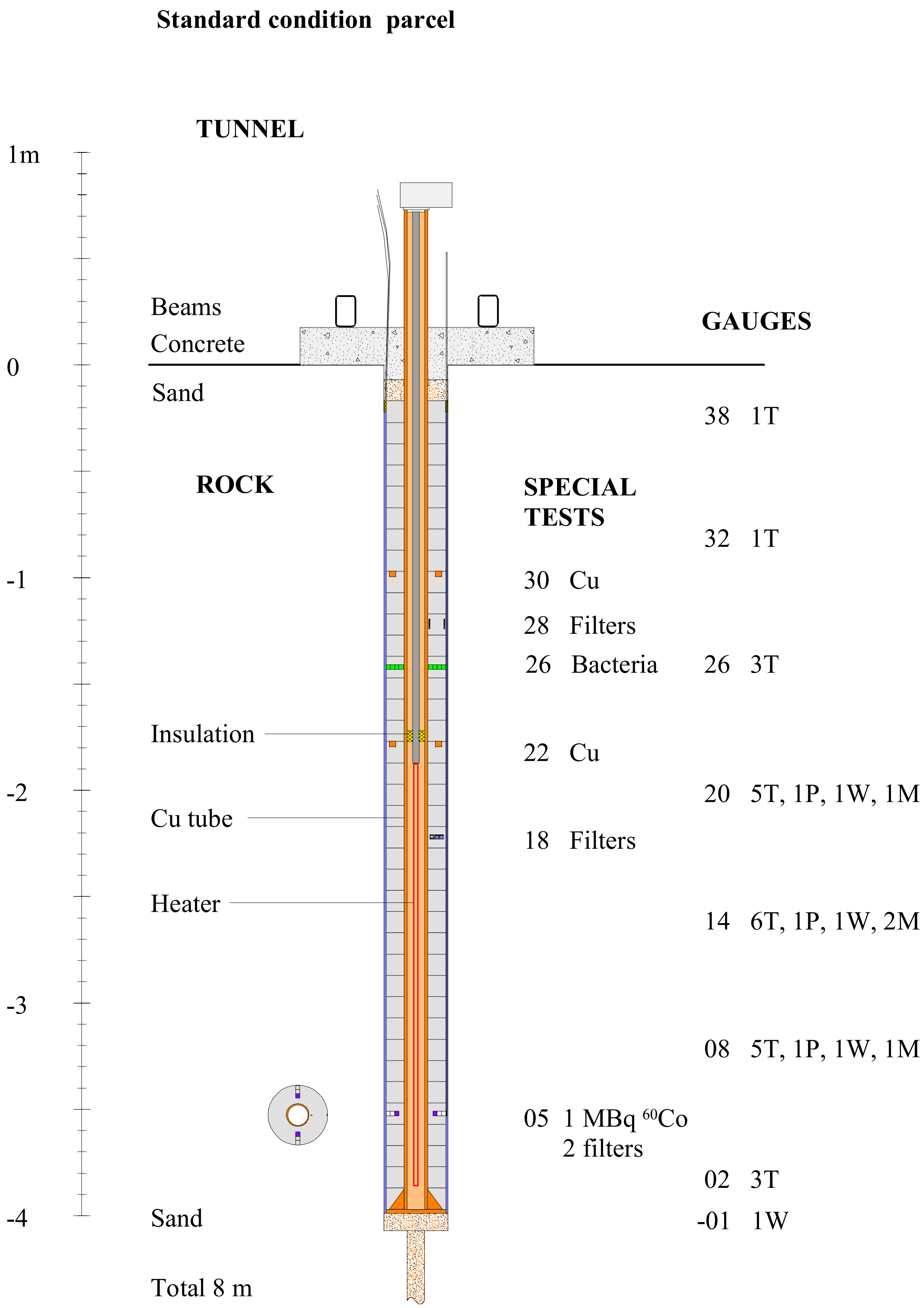

Figure 3-4. *Cross-section view of an S-type parcel. The first figures in column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.*

Adverse conditions in this context refer to high temperatures, high temperature gradients over the buffer, and additional accessory minerals leading to i.a. high pH and high potassium concentration in clay pore water. The central copper tubes are equipped with heaters in order to simulate the decay power from spent nuclear fuel. The heater effect are regulated or kept constant at values calculated to give a maximum clay temperature of 90°C in the standard tests and in the range of 120 to 150°C in the adverse condition tests.

Each parcel contains 25 thermocouples, 3 total pressure gauges, 3 water pressure gauges, 4 relative humidity sensors, 7 filter tubes, and 12 water sampling cups. The power is regulated and temperature, total pressure, water pressure and water content are continuously being measured.

At termination of the tests, the parcels are extracted by overlapping core-drilling outside the original borehole. The water distribution in the clay is determined and subsequent well-defined chemical, mineralogical analyses and physical testing are performed.

Present status

The 1-year pilot test parcels (A1, S1) were installed during 1996. They have been retrieved, analysed and reported /Karnland et al., 2000/.

During autumn 1999 the long-term test parcels (A2, A3, S2, S3) and the additional 1-year parcel (A0) were installed in the G-tunnel.

The power in parcel A0 was turned off in October 2001 and the parcel was released from the rock by overlapping percussion drilling, approximately 20 cm outside the bentonite. The release operation was complicated and took around three weeks to complete. When the parcel was fully released and uplift the first cut up was made on site. The material was sent to laboratories for the various planned tests and analyses. Preliminary results concerning water content, degrees of saturation and water chemistry are presently at hand.

Scope of work for 2002

The main task during 2002 is to examine the field-exposed material from the A0 parcel. Tests and analyses of the A0 bentonite material copper coupons and tracer test material will continue during the spring and summer. This work is presently being made at Clay Technology in Lund with respect to the bentonite mineralogy and physical properties, KTH in Stockholm with respect to diffusion of the tracer elements ^{60}Co and ^{134}Cs, VTT in Helsinki with respect to water chemistry, and at Studsvik the copper samples are, analysed with respect to corrosion. Characterisation of the original bentonite material in the parcels will be made in parallel to the exposed material. The work is planned to be reported during the autumn of 2002 in a SKB Technical Report.

Water pressure, total pressure, temperature and moisture in the 4 remaining parcels are continuously being measured and stored every hour. These data are being checked monthly, and the results are planned to be analysed more carefully and reported in April and October.

Preparatory gas tests will be made if the bentonite material is fully water saturated in one of the standard type parcels. At present the S2 parcel seems most likely in this respect.

3.7 Pillar Stability Experiment

Background

Very little research on the rock mass response in the transitional zone (accelerating frequency of micro-cracking) has been carried out. It is therefore important to gain knowledge in this field since the spacing of the canister holes gives an impact on the optimisation of the repository design.

A Pillar Stability Experiment is therefore initiated in Äspö HRL as a complement to an earlier study at URL performed by AECL in Canada. AECL's experiment was carried out during the period 1993-1996 in an almost unfractured rock mass with high in-situ stresses and brittle behaviour. The major difference between the two sites is that the rock mass at Äspö is fractured and the rock mass response to loading is elastic. The conditions at Äspö HRL therefore make it appropriate to test a fractured rock mass response in the transitional zone.

Objectives

The pillar stability experiment is a rock mechanics experiment which can be summarised in the following three main objectives:

- Demonstrate the capability to predict spalling in a fractured rock mass.
- Demonstrate the effect of backfill (confining pressure) on the propagation of micro-cracks in the rock mass closest to the deposition hole.
- Comparison of 2D and 3D mechanical and thermal predicting capabilities.

The project consists of two different work packages of which the first is the modelling and prediction work and the second is the excavation of rock and installation of instruments and heaters.

The project is divided into four different phases:

- Phase 1 is a feasibility study and preliminary design of the experiment. The expected outcome of the feasibility study is the location of the new tunnel, the experimental design and to demonstrate that the chosen design will give high stresses enough in the pillar. The feasibility study shall also give a rough estimation about what kind of instrumentation that will be needed.
- Phase 2 shall result in a final experiment design. Phase 2 also includes exploratory core drilling in the extension of the new experiment tunnel. When the test results from the cores in the proposed experiment location are ready they will be used for the numerical modelling. The numerical models will be completed and reported before the installation of the instrumentation starts.
- Phase 3 comprises all the work in the new tunnel including the instrumentation.
- Phase 4 comprises the heating part of the experiment. After completion of the experiment, compilation and analyses of sampled data will be summarised and reported.

Experimental concept

To achieve the objectives a new short tunnel will have to be constructed in Äspö HRL to ensure that the experiment is carried out in a rock mass with a virgin stress field. In the new tunnel a vertical pillar will be constructed in the floor. The pillar will be designed in such a way that spalling will occur when the pillar is heated.

To create the pillar two vertical holes will be drilled in the floor of the tunnel so that the distance between the holes is 1 m. To simulate confining pressure in the backfill (1 MPa), one of the holes will be subjected to an internal water pressure via a liner.

Thermistors and Acoustic Emission will be used to monitor the experiment. Only these two kinds of monitoring together with visual inspection are necessary to assess the outcome of the experiment.

Present Status

The project was initiated in 2001 and the feasibility study and preliminary design (Phase 1) is completed.

Scope of work 2002

The main activities during 2002 are:

- Compilation and reporting of the feasibility study and the preliminary design of the experiment (Phase 1).
- Initiate the exploratory core drilling with geological and hydrogeological characterisation including thermal laboratory tests on cores. The outcome of this characterisation will be the last information needed to determine if the selected area is suitable for the experiment.
- Determination of location of the instrumentation and the heaters as well as specifications on all the equipment to be used.
- Numerical modelling with three different codes (UDEC, FRACOD and PFC3D) to predict the outcome of the experiment.
- Selection of technique for excavation of the tunnel and holes.
- Compilation of a detailed budget and work plan for Phase 3.

3.8 Low-alkali cementitious products

Background

The use of cement based products in the deep repository will cause high pH (pH>11) in the near-filed of the repository, which is unfavourable for the long-term performance of the repository. The result of a feasibility study performed during 2002 is a recommendation to initiate a thorough study to verify the usefulness of low-alkali cementitious products in the repository. Such a study has been initiated in co-operation with Posiva.

Objectives

The objective of the verification of the usefulness of low-alkali cementitious products in the repository is to develop recipes for cementitious products to be used as grouting and anchoring of rock bolts and to demonstrate the usage in a field experiment. In addition, the influences of low-alkali cementitious products on the repository performance are to be evaluated.

The project is performed in a number or work packages:

1. Influences on the repository performance, including a compilation of knowledge concerning copper corrosion, fuel dissolution, radionuclide chemistry, and bentonite degradation.
2. Basic understanding, including leach tests and development of cement paste recipes.
3. Fabrication of cement paste with pH<11 leachate.
4. Rock bolting, including selection of appropriate mortar.
5. Grouting, including laboratory experiments and demonstration of requirements on the grout and the geological conditions at the field site.
6. Small field tests in Äspö HRL where grouting and mortar for anchoring of rock bolts are tested.
7. Project managing and planning of next stage.

Scope of work 2002

The project was initiated in December 2001 and will according to current plans be concluded and reported in the end of 2002.

3.9 KBS-3 method with horizontal deposition

Background

The KBS-3-method based on the multi-barrier principle is accepted by the Swedish authorities and the government as base for the planning of the final disposal of the spent nuclear fuel. The possibility to modify the reference method and make serial deposition of canisters in long horizontal drifts instead of vertical deposition of single canisters in the deposition hole has been investigated since early nineties. One reason for proposing the change is that the deposition tunnels are not needed if the canisters are disposed in horizontal drifts and the excavated rock volume and the amount of backfill can be considerably reduced. Another reason is that it is easier to verify the quality of the near zone around the canister when the bentonite and the canister is assembled into a prefabricated disposal package in a reloading station.

Late 2001 SKB published an R&D program for the KBS-3 method with horizontal deposition (KBS-3H), see Figure 3-5. The R&D program is divided into four parts: Feasibility study, Basic design, Construction and testing at the Äspö Hard Rock Laboratory, and Evaluation.

The R&D program is carried through by SKB in co-operation with Posiva.

Objectives

The gains, due to smaller volume of excavated rock, in term of environmental impact in particular, but also cost, make the KBS-3 method with horizontal deposition (KBS-3H) an interesting variant. Great efforts are, however, required developing the variant.

The objective of the first part of the project, the feasibility study, is to evaluate if horizontal deposition is an alternative technique for deposition, and if so, to give SKB and Posiva a basis for continued evaluation of KBS-3H as a variant. The feasibility study focuses on differences compared to the reference concept KBS-3V. Highlighted tasks are the deposition technique and the function of the buffer.

Scope of work 2002

The feasibility study was initiated during the fourth quarter 2001 and will be concluded during 2002. It will be followed by a decision concerning the continuation of the project in accordance with the R&D program. The feasibility study comprises a number of subprograms:

– Geoscientific studies.

– Buffer performance (including a laboratory test with two disposal canisters in scale 10:1).

– Sealing of deposition drifts.

– Retrieval.

– Rock characterisation and grouting.

– Drilling technology - tunnel boring machine (TBM).

– Drilling technology - water hammers in a cluster frame.

– Deposition technique.

– Preliminary safety assessment.

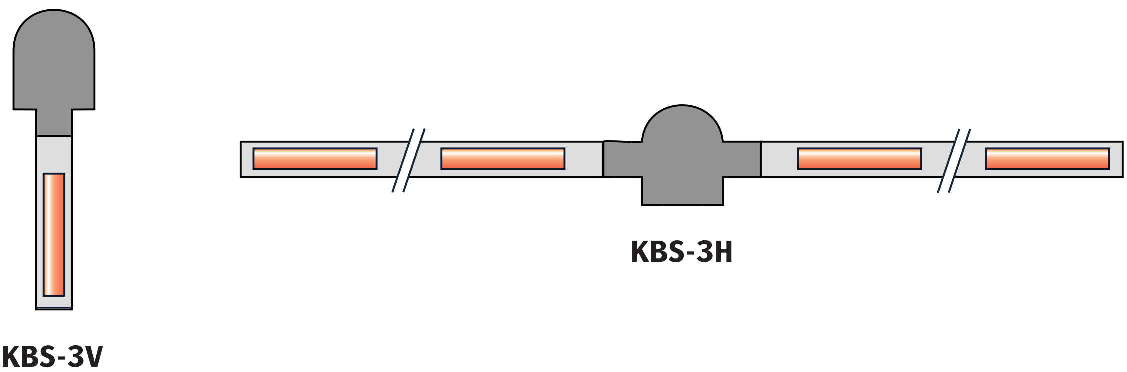

Figure 3-5. *Schematic illustrations of variants of the KBS-3 method.*

3.10 Cleaning and sealing of investigation boreholes

Background

Investigation boreholes are drilled during site investigations and detailed characterisation in order to obtain data on the properties of the rock. These boreholes must be sealed, no later than at the closure of the deep repository, so that they do not constitute flow-paths from repository depth to the biosphere. Sealing of the boreholes means that the conductivity in the borehole is no higher than that of the surrounding rock. Cleaning of the boreholes means that instrumentation that has been used in the boreholes during long time-periods, in a sometimes aggressive environment, is removed.

Sealing of boreholes with cementitious materials is commonly used in construction work and can be performed with well-known techniques. Earlier studies, e.g. the Stripa project, have shown that sealing with cementitious material include a potential risk for degradation due to leaching and the sealing can not be guaranteed over time-periods longer than hundreds of years. Another opportunity is to use swelling clay materials, such as compacted bentonite blocks or bentonite pellets. Sealing with bentonite blocks has been tested in the framework of the Stripa project, in boreholes with a length of 200 m, with very promising results. A further development of this technique is however required to show that boreholes with lengths of up to 1 000 m can be sealed.

Since most of the investigation boreholes are instrumented, reliable technique is also needed to clean boreholes so that they can be sealed.

Objectives

The main objective of this project is to identify and to demonstrate, in field experiments, the best available techniques for cleaning and sealing of investigation boreholes. The project consists of two phases.

Phase 1 comprises:

- Inventory of known methods for sealing of boreholes with potential to be used for investigation boreholes. The inventory considers both cementitious materials and swelling clay materials.
- Performance of complementary laboratory experiments with sealing materials to obtain as high density and as low conductivity as possible.
- Investigation of the status of two instrumented boreholes at Äspö HRL (KAS 6 and KAS 7).

Phase 2 comprises:

- Field experiments in boreholes at Äspö to test different techniques for cleaning and sealing of boreholes.

Scope of work 2002

The project will be initiated in May 2002 and Phase 1 will be completed and reported at the end of the year.

3.11 Task Force on Engineered Barrier Systems

Background

A Task Force on Engineered Barrier Systems has also been initiated. The preparatory workshop suggested that the focus should be on the water saturation process in buffer, backfill and rock. Since the water saturation process is also a part of the modelling work in the Prototype Repository, the work of the Task Force was consequently linked together with modelling work within the EC-project concerning the Prototype Repository. The difference is that GRS (Germany) and ANDRA (France), which are not participating in the EC-project, are participating in the modelling work being undertaken by the Task Force. They are being given access to the same data as the participants in the EC-project. The relevant task is:

Task 1 Thermo-hydro-mechanical modelling of processes during water transport in buffer, backfill and near-field rock.

Scope of work

The goal is to initiate and carry out Task 1. New tasks will gradually be defined in co-operation with the international organisations that are participating in the Äspö project.

4 Äspö facility

4.1 Facility operation

Background

The main goal for the operation is to provide a safe and environmentally correct facility for everybody working or visiting the hard rock laboratory. This includes preventative and remedy maintenance in order to withhold high availability in all systems as drainage, electrical power, ventilation, alarm and communications in the underground laboratory.

Scope of work for 2002

A plant supervision system was taken into operation in 2000. This has considerably increased the possibility to run the facility in a safe and economic way. In 2002 several systems are to be monitored and if possible optimised. The goal is to reach 99% availability in the underground-related systems during 2004.

The long-term rock control and reinforcement program, initiated in year 2000, continues to ensure safe and reliable rock conditions. The decision, concerning any measures, will be taken after inspection.

Work on increased fire safety is also this year of concern. In the beginning of 2002 an extension of the fire alarm system underground is be made. Safety-related education and fire fighting training is held in co-operation with the local fire brigade.

The automatic registration and object-monitoring system is taken into operation having the benefit of increasing personnel safety underground. Development of the system starts with the objective to control the ventilation need underground in relation to the number of vehicles and engines being underground. A system is installed for remote control and diagnose of hoist performance, which has a direct connection to the hoist manufacturer.

The existing ventilation control will be exchanged during the autumn and a frequency controlled speed control will be installed. The aim is to decrease the energy consumption and costs for maintenance.

The existing UPS-system (uninterruptible power supply) will be complemented with an additional system. The extension means that the data servers and the other critical systems e.g. the switchboard and fire alarm will be connected to separate UPS-systems.

The decision to host the staff of the Oskarshamn site investigation project results in a need for additional office space besides the number of offices that were provided in the temporary barracks. New offices are probable created more permanently, which suggests additional permanent rooms in conjunction with the existing building in the Äspö Research Village.

The road to Äspö was coated during 2001 and some additional road works are planned during 2002 e.g. the bridge over Lindsströmmen and the road from Ävrö village to Lindströmmen.

4.2 Hydro Monitoring System

Background

An important part of the Äspö facility is the administration, operation, and maintenance of instruments as well as development of investigation methods.

The Hydro Monitoring System (HMS) collects data on-line of groundwater head, salinity, electrical conductivity of the water in some borehole sections and, Eh and pH in some other boreholes. The data are recorded by numerous transducers installed in boreholes on Äspö as well as in boreholes located in the tunnel.

All data are transmitted to the main office at Äspö, by radio or modems. Weekly quality controls of preliminary groundwater head data are performed. Absolute calibration of data is performed three to four times annually. This work involves comparison with groundwater levels checked manually in percussion drilled boreholes and in core drilled boreholes, in connection with the calibration work.

As an effect of the excavated tunnel, the groundwater levels in the core drilled boreholes in the vicinity of the tunnel have been lowered up to 100 meters. Because of this the installations in the boreholes, e.g. the stand pipes (plastic tubes) in the open boreholes have been deformed. This makes it sometimes impossible to lower pressure transducers in the tubes or to lower manual probes for calibration purposes. Development and testing of new types of tubes is in progress. An evaluation of the groundwater monitoring system used at Äspö HRL is needed before a new similar system will be set up at candidate sites for the deep repository.

Measuring system

The measuring system, which is incorporated in the HMS, is located in the tunnel (with substations at sections 690, 1190, 1645, 2162, 2511, 3007, 3107, 3385 and 3510 m). Groundwater inflow to the tunnel is measured at intervals in the tunnel by dams and weirs.

The inflow of water into the different shafts is collected with the aid of a weir and a Thomson measuring device for flow determination. At the ramp positions at 220, 340, and 450 m, the measuring stations are installed for data sampling from the substations.

Scope of work for 2002

- Transducers for weir levels in PG5 will be changed to an ultrasonic type.
- New measurement points in the tunnel will be instrumented and connected to the HMS-system.
- The equipment in the surface borehole KLX01 will be renovated.
- Pressure transducer for sampling of pressure in the packer system in boreholes in the tunnel will be installed.

4.3 Program for monitoring of groundwater head and flow

Background

The HMS network includes besides the Äspö HRL system, surface boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen and some boreholes on the mainland at Laxemar.

The system has evolved through time, expanding in purpose and ambition. The monitoring of water levels started in 1987 while the computerised HMS was introduced in 1992. The number of boreholes included in the network has gradually increased. The tunnel excavation started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992.

Construction of the Äspö HRL began in October 1990 and was completed during 1995. The tunnel excavation began to impact the groundwater head during the spring 1991.

Objectives

The scope of maintaining such a monitoring network has scientific as well as legal grounds:

- It is a necessary requirement in the scientific work to establish a baseline of the groundwater head and groundwater flow situations as part of the site characterisation exercise. That is, a spatial and temporal distribution of groundwater head prevailing under natural conditions (i.e. prior to excavation).
- It is indispensable to have such a baseline for the various model validation exercises, including the comparison of predicted head (prior to excavation) with actual head (post excavation).
- It was conditioned by the water rights court, when granting the permission to execute the construction works for the tunnel, that a monitoring program should be put in place and that the groundwater head conditions should continue to be monitored until the year 2004 at the above mentioned areas.

Monitoring network

To date the monitoring network comprise boreholes of which many are equipped with hydraulically inflatable packers, measuring the pressure by means of transducers. The measured data are relayed to a central computer situated at Äspö village through cables and radio-wave transmitters. Once a year the data are transferred to SKB's site characterisation database, SICADA. Manual levelling is also obtained from the surface boreholes on a regular basis. Water seeping through the tunnel walls is diverted to trenches and further to 21 weirs where the flow is measured.

Scope of work for 2002

The operation of the monitoring system will maintain the monitoring points from the previous year and no additional point are planned. The system will continue to support the experiments undertaken and meet the requirements stipulated by the water rights court.

4.4 Program for monitoring of groundwater chemistry

Background

During the Construction Phase of the Äspö HRL, different types of water samples were collected and analysed with the purpose of monitoring the groundwater chemistry and its evolution as the construction proceeded. The samples were obtained from boreholes drilled from the ground surface and from the tunnel.

Objectives

At the beginning of the Operational Phase, sampling was replaced by a groundwater chemistry monitoring programme, aiming at a sufficient cover of the hydrochemical conditions with respect to time and space within the Äspö HRL. This program is designed to provide information to determine where, within the rock mass, the hydro-geochemical changes are taking place and at what time stationary conditions are established.

Scope of work for 2002

The annual water sampling campaign is scheduled to take place in September - October.

4.5 Geo-scientific modelling

Background

Based on pre-investigations geological, geomechanical, geohydrological and hydro-geochemical models were made over Äspö HRL. During the Construction Phase the models were successively updated based on characterisation data obtained from 1986 until 1995. This work resulted in the Äspö96 models /Rhén et al., 1997/.

The GeoMod project will update the existing models by integrating new data collected since 1995. The major part of the new data has been collected during the operational phase for the different on-going experiments. The new data have been produced in the lower part of the Äspö HRL. The updated model will focus on a volume including the tunnel spiral volume from about 340 m to about 500 m.

Objectives

The aim of the GeoMod project is to construct geological, geomechanical, geohydro-logical and hydrogeochemical models of Äspö. Specifically the modelling exercise will update the present models Äspö96 /Rhén et al., 1997/. This project will include the additional tunnel data and understanding generated from the various experiments and activities at the Äspö HRL since 1995. With regard to the rock mechanical model of Äspö a project has recently been completed, which will constitute the basis for the rock mechanical model of Äspö as proposed for the GeoMod project.

Scope of work 2002

Most new data have been collected during the operational phase for different experi-ments conducted in the tunnel. New data have been collected in the lower part of the Äspö HRL. The updated model will focus on a volume including the tunnel spiral.

The work is perceived to be undertaken in overlapping steps:

- Assess the existing data/models within each geoscientific discipline; geology, hydrogeology, rock mechanics and hydrogeochemistry.
- Sampling of selected data may be done in order to appraise the data and check its quality and to fill the gap between well characterised rock volumes. The starting point is to utilise results from the different projects conducted at Äspö. The review of existing data as a whole is not contained in the project.
- Interactively construct a geoscientific model for each discipline, which will form the basis for an integrated site descriptive geoscientific model.

The modelling is contained within a common virtual cube with 1 km side length extending from +50 m to -1000 m above sea level in elevation.

5 International co-operation

5.1 General

Eight organisations from seven countries are from January 2002 participating in the Äspö Hard Rock Laboratory.Most of the organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several organisations are participating in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, which is a forum for co-operation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. Table 6-1 shows the scope of each organisation's participation under the agreements.

The co-operation is based on separate agreements between SKB and the organisations in question. The participation by JNC and CRIEPI is regulated by one agreement and one delegate in the International Joint Committee represents the two companies.

ANDRA, Posiva, ENRESA, JNC and SKB are co-operating under a special multilateral agreement regarding the TRUE Block Scale experiment. Nirex has left the co-operation work during 2001.

A Task Force on Engineered Barrier Systems has also been initiated. It will concentrate on the water saturation process in buffer, backfill and rock. Since the water saturation process is also a part of the modelling work in the Prototype Repository, the work of the Task Force has been linked together with the modelling work within an EC-project concerning the Prototype Repository.

SKB is through Repository Technology co-ordinating two EC contracts and in addition SKB takes part in several EC projects of which the representation in five projects is channelled through Repository Technology.

Table 6-1. International participation in Äspö HRL.

Organisation	Participation
Agence Nationale pour la Gestion des Déchets Radioactifs, **ANDRA**, France.	Tracer Retention Understanding Experiments (TRUE Block Scale) Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository Temperature Buffert Test – A test in the second hole in the Canister Retrieval Tunnel consisting of a bentonite column with heaters inside for creation of a line heat source

Table 6-1. International participation in Äspö HRL. (cont.)

Organisation	Participation
Bundesministerium für Wirtschaft und Technologie, **BMWi**, Germany	Radionuclide Retention Project (Acitinide experiments) Colloid Project Microbe Project Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository
Empresa Nacional de Residuos Radiactivos, **ENRESA**, Spain	Tracer Retention Understanding Experiments (TRUE Block Scale) Task Force on Modelling of Groundwater Flow and Transport of Solutes Backfill and Plug Test Prototype Repository
Japan Nuclear Cycle Development Institute, JNC, Japan.	Tracer Retention Understanding Experiments (TRUE Block Scale Continuation) Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository
The Central Research Institute of the Electronic Power Industry, CRIEPI, Japan	Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository Voluntary project on groundwater dating – Validation of groundwater dating methods and evaluation of stability in groundwater environments after tunnelling.
Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, NAGRA, Switzerland	Task Force on Modelling of Groundwater Flow and Transport of Solutes
Posiva, Finland.	Tracer Retention Understanding Experiments (TRUE Block Scale) Colloid-project Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository Long Term Test of Buffer Material Pillar Stability Experiment
USDOE Carlsbad Field Office/Sandia National Laboratories, USA	Task Force on Modelling of Groundwater Flow and Transport of Solutes

5.2 Scope of work 2002 by participating organisations

The international organisations are taking part in the projects and experiments described under the headings "Natural barriers" and "Demonstration of technology for and function of important parts of the repository", see Chapters 2 and 3 respectively. In the following sections a more detailed description of the scope of work for 2002 to be performed by the different organisations is given.

The contribution of NAGRA is fully integrated in the work performed within the Task Force on Modelling of Groundwater Flow and Transport of Solutes and no separate description of their work is therefore given below.

5.2.1 ANDRA

Background

L'Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA) provides since 1992 experimental and modelling support to the Äspö HRL with emphasis on site characterisation to complete research activities in France.

ANDRA's recent contributions focused on:

- Modelling work within the Task 5 of the Äspö Task Force on Groundwater Flow and Transport of Solutes concentrated on hydro-chemical changes caused by the construction of the Äspö HRL
- TRUE Block Scale experiment with the design, performance and interpretation of non-sorbing tracer tests and modelling efforts.

ANDRA has installed one device in each deposition hole in the Prototype Repository (Section I) for measurement of the displacement of the interface between the top bentonite block and the backfill. This interface is originally located 1 m below the tunnel floor. The device is based on the communication vessel principle and consists of a liquid-filled tank, which is placed in the interface and open hoses running out to the adjacent tunnel, where the change in liquid surface is measured.

Objectives

Prime objectives of ANDRA were and still are to enhance the understanding of flow and transport in fractured granitic rock and to evaluate experimental and modelling approaches in view of site characterisation of a French site.

In conjunction with SKB's development of major experiments related to parts of the repository system, new objectives appear concerning the near-field, and ANDRA is enhancing the understanding and modelling of the engineered barrier systems behaviour. An additional topic is comparing the functions of repository systems for either spent fuel or reprocessed vitrified HLW.

Scope for 2002

– Participation in modelling in Task 6 of the Äspö Task Force, with the aim of bridging site characterisation data and approach and modelling of long-term safety.

– Contribution through ITASCA to the modelling and supporting of the TRUE Block Scale Continuation test.

– Participation in the Prototype Repository with modelling of the THM behaviour in the Canister Retrieval Test (controlled saturation).

– Temperature Buffer Test. Plans are advanced for a temperature test in full-scale with buffer and canister/heaters in a geometry that is based on the French canister dimension and thermal power and the diameter and depth of the second simulated deposition hole in the Canister Retrieval tunnel. The test will be subject to ANDRA's decision, and may in case of a go ahead be installed early 2003. The set-up is planned to provide a sister geometry to the actual Canister Retrieval Test. This is done in order to facilitate the interpretation of data and the robustness in conclusions on the capability of ANDRA's THM model to represent processes taking place during saturation.

5.2.2 BMWi

In addition to the research carried out in Germany for final disposal in salt formations, the purpose of the co-operation in the Äspö HRL programme is to complete the knowledge on other potential host rock formations for radioactive waste repositories. The work addresses groundwater flow and radionuclide transport, two-phase flow and transport processes, and development and testing of instrumentation and methods for detailed underground rock characterisation. Six research institutes are performing the work on behalf of and funded by Bundesministerium für Wirtschaft und Technologie (BMWi): BGR, FZK, FZR, GRS, Uni Stuttgart, and TU-Clausthal.

Two-phase flow

In co-operation with KTH a project is being performed to further improve the numerical tools for calculating gas-water flow in fractured and porous media. The aims are to further develop the methods to describe two-phase flow processes in single fractures and to develop up-scaling methods for transferring the constitutive relations from micro-scale to macro-scale. Furthermore, data from the Äspö HRL are used to generate geostatistical models. In 2002, up-scaled constitutive relationships will be combined with the 3D model for two-phase flow in a fracture matrix system. Several simulations will be done in order to determine the effect of the up-scaled parameters derived from different variograms of aperture distributions. One of the fracture systems to be generated will be based on provided data /Jarsjö et al., 2001/.

Prototype Repository

In the frame of the Prototype Repository project, electrical resistivity measurements will be conducted in boreholes and backfilled tunnel sections in order to investigate time-dependent changes of water content in the backfill, in the buffer, and in the rock. In these investigations, advantage is taken of the dependence of the electrical resistivity of rocks on fluid content, porosity, and fluid resistivity. In order to correlate the resistivity with the fluid content, the field measurements will be accompanied by laboratory tests. The installation of the first electrode array in the inner section (Section 1) and of the measurement system in the data acquisition room was completed in October 2001. The electrode array between deposition holes 5 and 6 in the outer section (Section 2) will be installed in January 2002. The array in the buffer of deposition hole 5 will be installed in May 2002, and the array in the backfilled Section 2 will be installed in June/July 2002. The laboratory tests have been extended to include the Milos bentonite, which was selected in 2001 as drift backfill material. The extended laboratory tests will be terminated by mid 2002.

An additional contribution to the Prototype Repository project consists of THMC modelling aimed to determine transport parameters within the repository. For this purpose, available finite-element computer programs will be used, further developed and expanded by integrating other available programs into the system. In 2002, a number of in-situ measurements are planned to determine the EDZ in order to underpin the THMC calculations. A series of laboratory experiments are planned to measure parameters relating to saturation, thermal conductivity, hydraulic conductivity, non–isothermal capillary pressure/saturation relationships, threshold pressure, and also the sorption properties of Sr^{2+} and Cs^{+} in MX-80 Bentonite. These data are required for the calculations planned in 2002 using the programs ROCKFLOW (two-phase flow, material transport), ADINA (mechanics, temperature, hydraulics), TOUGH2 (temperature, two-phase flow) and PHREEQC (chemistry, transport). The THMC calculations will focus on saturation and build-up of stresses in backfill and buffer, taking into account the effect of temperature changes.

Within the frame of the Prototype Repository project, modelling of resaturation processes in the bentonite buffer is being performed. In order to simulate resaturation by vapour diffusion, the importance of the basic resaturation mechanisms will be investigated more closely with the help of a supplemental model, which will be developed in 2002. Data concerning the time dependent distribution of water will be obtained from laboratory resaturation experiments and analysed using the codes developed in this project.

Radionuclide Retention Experiments

Transport and retention of typical elements in micro-fractured rock around larger fractures are studied, with the objectives to determine distribution and characteristical parameters (volume and internal surface) for altered fracture zones.

Investigations of the distribution of actinides and the sorption behaviour along the flow-path are carried out with different methods: The abraded material gained by cutting the slices is acidulated and the actinide concentration is measured by ICP-MS. In the solid material of the slices the actinide concentration is analysed by means of coupled laser ablation ICP-MS techniques and radiographic methods. Visually, fractures could be detected only partly in a first set of cores. This finding indicates a very complex flow-path.

Experiments with new cores in CHEMLAB will be started as soon as possible. The new cores have well-developed fractures and their flow geometry is less complicated. The duration of new experiments is also scheduled to be about 3 months. Using one of these new cores, one experiment will cover the migration of uranium and technetium. Based on tomographic analyses, 2D transport will be computed. In order to model the actinide behaviour, coupled transport/reactive/sorption models such as HydroBioGeoChem will be applied.

Colloid Project

Groundwaters present in Äspö HRL are analysed with respect to their background colloid concentrations. The in-situ measurements are performed by means of the mobile LIBD (Laser Induced Breakdown Detection) device developed by FZK/INE. Application of LIBD requires a specific detection cell, which can be operated under representative hydrostatic pressures of about 3 MPa. The background colloid measurements performed in October/November 2001 will be evaluated in early 2002. Based on a new detection method, additional calibration measurements will be performed. Planning for a colloid migration experiment will start in 2002.

Microbe Project

A project is performed addressing (i) the interaction of actinides with relevant bacteria found in Äspö groundwater, (ii) quantification of actinide bonding on micro-organisms in dependence of the chemical conditions in the groundwater, and (iii) characterisation of the actinide complexes/compounds formed by interaction with microbes. The project includes the continuous cultivation and quality control of the used Desulfovibrio-äspöensis biomass. Investigations of the interaction of the Desulfovibrio-äspöensis biomass with the selected actinide elements uranium and curium will start in 2002.

5.2.3 ENRESA

Backfill and Plug Test

ENRESA's contribution to the Backfill and Plug Test are devoted to:

- Development and testing of a dynamic pore-pressure sensor, based on the piezocone principle, for the direct, in-situ measurement of the backfill saturated permeability in selected zones.
- Modelling of the hydro-mechanical processes of a section of the backfill, including the hydration process and the hydraulic tests to be performed.

The dynamic pore-pressure sensors and the corresponding measurement system were installed during 1999 in the backfill (in Section A4). The spatial distribution of the 13 sensors installed was selected seeking to capture potential gradients of hydraulic conductivity derived from possible density gradients between the inner and outer parts of the backfill. The permeability map of the saturated backfill to be obtained with the pore-pressure sensors will be compared to the global permeability value estimated by back-analysis from the flow test to be done also under saturated conditions.

Regarding modelling, a few simulations of the hydration process have already been performed using the finite element code CODE_BRIGHT. As expected, it has been found that the time required for saturation is very sensitive to the parameters governing the flow equations. Due to the scattering in the laboratory experiments, the reliability of the values adopted for those parameters has been considered not enough to make reliable predictions. Therefore, additional laboratory tests, already initiated in 2001, will be done during 2002.

The existing gradients of salt concentration in the water of the mixture and in the hydration water have complicated the modelling work. An important effort is being made to incorporate such effects in the simulations. In fact, some of the laboratory tests being performed will help understanding the coupling between hydraulic properties and water salt concentration. The effect of this coupling has been highlighted because in the Zedex tunnel at Äspö, water with different salt concentrations is being mixed in the backfill.

The planned activities are based on the Clay Technology previsions: buffer saturated by September 2002. So only the maintenance of the permeability monitoring system is foreseen at the HRL during the year 2002.

The ongoing laboratory work to be finished by March 2002 is:

a) Odometer tests on Rowe cells, in backfill samples with two different dry densities, saturated with distilled water and water with a salt content of 1.6% (sodium and calcium chloride, 50%-50%).

b) Water retention curves under free volume of a similar material (30/70 bentonite/sand), using distilled and salt water (the same conditions as before). Sand is used instead of grained granite to avoid big grain sizes.

c) Infiltration tests on 30/70 bentonite/crushed granite samples, using distilled water and salt water (the same conditions as before). Measurement of water content, sodium and calcium cations for different layers and at different hydration time.

Tests (a) and (b) are being performed by UPC, and Test (c) by CIEMAT. The results will be used to improve the knowledge on the parameters that control the hydration and flow problems. Due to the high heterogeneity of the material it has also been considered necessary to increase the number of experiments, in order to obtain a consistent average behaviour.

During 2002, after obtaining additional laboratory information and using field measurements of the hydration process, an attempt will be made to reproduce said process using the computer code. That information will allow performing back-analysis of the hydration seeking to obtain the parameters that give the best estimation of the problem variables, when compared with the measured values. This process is very important for the interpretation of the pulse tests scheduled for 2003.

Prototype Repository

ENRESA's contribution to the Prototype Repository Test concerns:

- Monitoring potential displacements of two of the canisters (Nº3 in Section I and Nº6 in Section II) during the entire life of the Test.

- To perform THM and THMC modelling of the experiment.

The sensors selected to monitor canister's displacement are fibre optic based, with no electronics inside, but a Thin Film Fizeau Interferometer, which receives a broadband white light and returns a wavelength, modulated light. Hence, it is assured that no electromagnetic interference will affect the readings. The selected sensor is a rugged version of the FOD 25 from Roctest, manufactured in Incoloy 825 because of the harsh working conditions, assuring water tightness and corrosion resistance. The dimensions of the sensor have been kept as small as possible to diminish perturbations in the system.

The displacement sensors for deposition hole Nº3 and the required measurement system were installed in 2001. Consequently the data acquisition and canister tracking monitoring is being done since then. The supervision and data management is carried out from a remote monitoring system located in the main offices of AITEMIN in Madrid. This system connects periodically via modem, for data transmission, with the local recording system installed on site. Reports will be generated periodically including graphical representation of the evolution of any measured displacement.

Regarding the modelling work, ENRESA will contribute with several analyses in a step by step approach. During 2001 T and TM analyses have been performed, to check the mesh and to compare with analyses performed by other groups. The next step is a THM simulation of one canister, focussing on the behaviour of the bentonite. Finally, a consideration of the chemical aspects involved in the bentonite buffer will be addressed in a preliminary simulation by the end of the project. UPC is performing the modelling with the in-house developed code CODE_BRIGHT.

According to the Project Plan the installation of the displacement sensors for hole Nº6 is foreseen for April 2002.

During 2002 the THM case proposed will involve different geometry and boundary conditions (i.e. 1D, 2D and 3D). Previous analyses done showed that, for many purposes, the axis-symmetric geometry of a deposition hole is a reasonable approximation. 3D geometry is very time consuming and only required for very particular cases, once all the boundary conditions and parameters have been fully checked.

A sensitivity analysis will be performed for the base case, considering the effects of basic parameters on the hydration time, one of the key variables that should be obtained from the modelling work. An attempt to simulate the effect of the pellets on the behaviour of the barrier will be also performed.

The results will be compared with the measurements available during 2002 specially concerning deposition hole Nº1 and preliminary conclusions about the validity of the modelling work will be adopted.

To support the modelling CIEMAT is performing some laboratory work concerning the THM characterisation of the MX-80 clay. The following determinations started during 2001 and will continue in 2002:

- Suction controlled odometer tests, with suctions up to 40 MPa and vertical loads of up to 9 MPa. The initial dry density and water content of the clay in the tests are those of the blocks manufactured for the in-situ test.
- Determination of the retention curve at constant volume of the MX-80 clay compacted at different dry densities and at 60 °C.

Additionally, the following tests, performed during 2001, will be analysed and reported:

- Hydraulic conductivity of the MX-80 compacted to different dry densities and permeated with water of different salinity.
- Retention curves at constant volume for different dry densities and salinity at 20 °C.

5.2.4 JNC and CRIEPI

JNC and CRIEPI have been active participants in the Äspö HRL Project since 1992, performing significant research on hydrology, transport, and engineering aspects of radioactive waste repository development. The scope of work planned for 2002 is summarised below.

Task Force on Modelling of Groundwater Flow and Transport of Solutes

JNC and CRIEPI will continue to participate in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.

During 2002, JNC's primary focus will be on developing and carrying out Task 6, "Performance Assessment Modelling Using Site Characterisation Data (PASC)". The objective of the participation in this task is to provide theoretical and experimental support for integration of site characterisation and performance assessment activities and techniques. JNC works on the Task Force subcommittee for development of the Task 6 specifications and the fracture network reference model. The plans are to carry out Task 6 simulations using both JNC/FracMan site characterization software and GoldSim PA software.

CRIEPI will apply original numerical codes FEGM and FERM to a computational work for the Task (6B2), and surmise and report results (Task 6A, 6B and 6B2). In addition, CRIEPI will start computational work (Task 6C). Furthermore, CRIEPI will investigate the site scale groundwater flow through inter-comparison between the ^{4}He concentration profile as a natural groundwater tracer and the simulated results of helium transport using the groundwater flow model focusing on the Äspö site.

Tracer Retention Understanding Experiments (TRUE Block Scale Continuation)

JNC will participate in the TRUE Block Scale Continuation Project during 2002 and they will be involved in all aspects of the project, including experimental design, analysis, and simulation. The participation is focused on addressing issues related to radionuclide retention processes, heterogeneity, network effects, fracture micro-structure, and compartmentalisation.

The Prototype Repository

JNC and CRIEPI will continue to participate in the Prototype Repository project.

During 2002, JNC will carry out coupled THM analysis (WP3h). They will calibrate the results of the two-dimensional prediction analysis and present the results of the three-dimensional prediction analysis. JNC will also perform back analysis of the three-dimensional prediction analysis using the monitored data and continue to investigate the feasibility for coupled THMC processes (WP3i). Results of the laboratory test of salt accumulation test will be presented as one example verification data for the THMC processes.

CRIEPI has developed a THM model, which can simulate the various interactive phenomena expected in an engineered barrier system. The developed model will be validated by using data from the in-situ experiment Long Term Test of Buffer Material (LOT) conducted in Äspö HRL and the model will be demonstrated through analyses in Prototype Repository project.

Voluntary Project on Groundwater Dating

CRIEPI has voluntarily collected groundwater for geochemical analyses at the Äspö site in September 2001 for the demonstration of groundwater dating methods and to evaluate long-term stability of groundwater environments during post tunnelling. The collected data is used to estimate groundwater residence times by measuring the dissolved ^{4}He content and ^{36}Cl concentration. CRIEPI has discovered a correlation between ^{36}Cl concentration and ^{4}He concentration in groundwater samples collected at the Äspö site in 1999. CRIEPI will estimate a reasonable groundwater residence time from this correlation in 2002. The last groundwater sampling mission was sent to Äspö HRL in September of 2001 to collect data of stable isotopes. CRIEPI will evaluate the stability in groundwater environments to the strong disturbance caused by tunnelling using data collected in the past seven years since 1995.

5.2.5 Posiva

Posiva and SKB signed a co-operation agreement in June 2001. The agreement covers co-operation within scientific and technical programmes and commercial services. Research and development of canister and encapsulation techniques, repository technology, and site evaluation are included. The following description comprises Posiva’s main activities at Äspö HRL in 2002.

Task Force on Modelling of Groundwater Flow and Transport of Solutes (Task 6)

From Posiva's point of view this project is useful since it may clarify the connection between site characterisation and performance assessment models. The confidence building on the applied transport models and concepts of the performance assessment is especially useful. In practice this means investigation of the structures and processes in bedrock that are relevant in the performance assessment scale.

Final results and reports on Tasks 6A and 6B will be presented during 2002. SKB will present the specification of Task 6C during 2002 and work on Tasks 6D and 6E will be started.

Tracer Retention Understanding Experiments (TRUE Block Scale)

From Posiva's point of view this project is useful for learning more about water flow and tracer transport in a network of fractures as a basis for flow and transport conceptualisation for performance assessment.

The evaluation of the TRUE Block Scale tracer tests is continued during 2002. An evaluation report of the tracer tests will be finalised at the beginning of 2002. The continuing work will be based on the process discrimination of the performed tracer tests and investigation of the basic matrix diffusion processes that are connected to the heterogeneity and properties of the immobile zones.

Colloid Project

Posiva participates in the planning and installation of the test arrangements as well as the construction of the equipment. Posiva also participates in the colloid and groundwater sampling and analysis.

The Prototype Repository

Posiva participates in the assessment of the planning and installation of the test arrangements and structures, and in the preparation of tunnel groundwater sampling and analysis. In addition the ground water balance at the interface between bentonite and bedrock will be modelled.

Long Term Test of Buffer Material

Posiva is participating in the project on Long Term Test of Buffer Material (LOT). The LOT test series aims at validating models and hypotheses concerning long-term processes in buffer material and related processes under conditions similar to those in a KBS-3 repository.

The research conducted in Finland pertains to the chemical processes occurring in bentonite and the chemical conditions in pore water and bentonite. The parcel of the one-year test (A0) was removed from the borehole during the second half of 2001. Studies on the bentonite have been started and will be completed in the year 2002. Decision on participation in research on the long-term tests (5 years and 20 years) will be taken later on the basis of results obtained from the first test.

5.2.6 USDOE CBFO/SNL

The working agreement between Sandia National Laboratories (SNL) and SKB in support of the contract to SKB from the U.S. Department of Energy (DOE) includes three separate tasks. These tasks are:

1. Validation of the multirate model using results from the TRUE-1 tracer tests conducted at the Äspö underground research laboratory.

2. Experimental visualisation of mass-transfer processes in low porosity rock.

3. Numerical experiments to understand the scaling of parameters defining mass-transfer from the tracer test scale up to the performance assessment scale. For each of the three tasks defined under the U.S. DOE-SKB contract, the objectives, experimental concept and scope are defined below.

Task Force on Modelling of Groundwater Flow and Transport of Solutes

Validation of the multirate model using TRUE-1 tracer test results

Work in 2001 completed the application of the multirate model to the Task 4 (STT-1, STT-1b and STT-2 tracer tests). Validation of the multirate model using TRUE-1 tracer test results will continue in 2002 under Task 6 where solute transport of radionuclides under ambient, non-pumping, conditions will be modelled at both tracer test and performance assessment time scales. This work presents a new opportunity in validation of the multirate model in that the model will be applied along multiple streamlines as determined from particle tracking through heterogeneous transmissivity fields. The hopes are to be able to use information on the heterogeneous transmissivity and porosity field to constrain the solute transport parameters in the multirate model along each individual streamline for different time and length scales. A summary of work to date on Task 6 will be presented in June at the next meeting of the Äspö Task Force. If these results are significant, then a journal article will be prepared describing the modelling activity.

Experimental visualisation of mass-transfer processes in low porosity rock.

The activities during 2002 comprise conclusion and documentation of the experiments with samples from Sweden and other countries. The experimental work will include determining the minimum pore size that can be visualised using computerised X-ray microtomography (CMT), the minimum concentration of tracer that can be detected using CMT and some more imaging of core samples, including cores from Äspö. The goal of this work will be to determine whether synchrotron X-ray microtomography is a satisfactory method for visualising diffusion through low-porosity crystalline rocks. The results will be documented in the form of a draft peer-review journal article.

Numerical Experiments for Understanding Scaling of Transport Parameters.

Work to date has involved the comparison of the multirate model, STAMMT-L to the SKB performance assessment model, FARF-31 results at the performance assessment scale. These models have been parameterised with estimations done on the much smaller scale STT-1 tracer tests. Boundary conditions and flow geometry from the SKB SR 97 calculations are used in the model comparison. The current plan is to finalise work in 2002 with the publication of a paper documenting the comparison of these calculations. Further work on scaling of transport parameters in 2002 will be conducted under Task 6 of the Äspö Task Force.

5.3 EC-projects

SKB is through Repository Technology co-ordinating two EC contracts: Prototype Repository and Cluster Repository Project (CROP). SKB takes part in several EC projects of which the representation is channelled through Repository Technology in five cases: FEBEX II, BENCHPAR, ECOCLAY II, SAFETI and PADAMOT. SKB will also be co-ordinator in the new project NET.EXCEL.

CROP

The project has the objective of assessing the experience from the various large-scale underground laboratories for testing techniques and aims specifically at comparing methods and data obtained from the laboratories for evaluating present concepts and developing improved ones. Several of these underground projects, which deal with disposal in crystalline rock, salt and clay formations, have been supported by the EC. The Cluster Repository Project (CROP) implies constitution of a forum - a cluster - for the intended evaluation and assessment, focusing on construction, instrumentation and correlation of theoretical models with field data, especially concerning engineered barrier systems.

CROP - Cluster repository project, a basis for evaluating and developing concepts of final repositories for high level radioactive waste	
Start Date: 2001-02-01	**End Date**: 2004-01-31
Coordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries:** Belgium, Canada, Finland, France, Germany, Spain, Sweden, Switzerland and USA

FEBEX II

The FEBEX project has the dual objective of demonstrating the feasibility of actually manufacturing and assembling an engineered barrier system and of developing methodologies and models for assessment of the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) behaviour within the engineered barrier system (near-field). FEBEX II consists in the extension of the operational phase of the FEBEX I in-situ test. The in-situ test is performed in a TBM-drift at the Test Site at Grimsel in Switzerland, where two full-scale canisters with electrical heaters have been installed horizontally. The canisters are surrounded by bentonite, pre-compacted into blocks possible to handle by man. The project also includes an extension, until quite-saturation, of the heating phase of a mock-up test; design and construction of a geochemical mock-up, and some complementary laboratory tests, as well as modelling works.

FEBEX II - Full-scale engineered barriers experiment in crystalline host rock phase II	
Start Date: 1999-07-01	**End Date:** 2003-12-31
Coordinator: Empresa Nacional de Residuos Radiactivos, Spain	**Participating countries:** Belgium, Czech Repblic, Finland, France, Germany, Spain, Sweden, and Switzerland

BENCHPAR

The purpose of the project is to improve the ability to incorporate thermo-hydro-mechanical (THM) coupled processes into Performance Assessment modelling. This will be achieved by three benchmark modelling tests: the near-field, up-scaling, and the far-field. Key THM processes will be included in the models. The first test will be on the resaturation of the buffer and interaction with the rock mass. The second test will determine how the up-scaling process impacts on performance assessment measures. The third test will model the long-term evolution of a fractured rock mass in which a repository undergoes a glaciation deglaciation cycle. A technical auditing capability will produce a transparent and traceable audit trail for the benchmark tests. The final deliverable will be a Guidance Document giving advice to EU Member States on how to incorporate THM processes into Performance Assessment.

BENCHPAR - Benchmark tests and guidance on coupled processes for performance assessment of nuclear repositories	
Start Date: 2000-10-01	**End Date**: 2003-09-30
Coordination: Royal Instituite of Technology (Dep. of Civil and Environmental Engineering), Sweden	**Participating countries:** Finland, France, Spain, Sweden and United Kingdom

ECOCLAY II

Cements will be used intensively in radioactive waste repositories. During their degradation in time, in contact with geological pore water, they will release hyper-alkaline fluids rich in calcium and alkaline cations. This will induce geochemical transformations that will modify the containment properties of the different barriers (geological media and EBS, i.e. clay-based engineered barriers). ECOCLAY I identified major geochemical reactions between bentonite and cement. ECOCLAY II investigates aspects such as radionuclides sorption, kinetics of the geochemical reactions, coupled geochemistry/transport processes, conceptual and numerical modelling and performance assessment. The whole hyper-alkaline plume will be studied within the project.

ECOCLAY II - Effects of cement on clay barrier performance, phase II	
Start Date: 2000-10-01	**End Date**: 2003-09-30
Coordinator: National Radioactive Waste Management Agency of France	**Participating countries:** Belgium, Finland, France, Germany, Spain, Sweden, Switzerland and United Kingdom

SAFETI

The aim of this project is to develop an innovative numerical modelling methodology that is suitable for excavation scale simulation of geological repositories. The method, termed “Adaptive Continuum/Discontinuum Code (AC/DC)” will be developed from existing algorithms. Full validation of the codes will be carried out using laboratory and in-situ acoustic emission and microseismic data collected in previous experiments. Further laboratory tests will be carried out during the proposed project for validation of the performance of both short- and long-term rock mass behaviour. The AC/DC represents a significant advance over current numerical modelling approaches and will have a wide range of application in waste repository engineering, including feasibility studies.

SAFETI - Seismic validation of 3-D thermo-mechanical models for the prediction of the rock damage around radioactive spent fuel waste	
Start Date: 2001-09-01	**End Date**: 2004-09-01
Coordination: The University of Liverpool (Dep of Earth Sciences), United Kingdom	**Participating countries:** France, Sweden and United Kingdom

PADAMOT

During the Quaternary global climate has alternated between glacial conditions and climate states warmer than the today. In northerly latitudes the potential for cold region processes to affect groundwater pathways, fluxes, residence times and hydrochemistry is significant, whilst for southern European localities the alternation between pluvial and arid conditions is equally important. PADAMOT will investigate the evolution of minerals and groundwater through these climate changes. The project will use advanced analytical techniques and numerical modelling tools. This palaeohydrogeological approach investigates processes that are significant for repository safety studies on length and time scales that cannot be simulated by experiment. Interpretations will be used to constrain the range of scenarios for conceptual model development and time-variant modelling in Performance Assessments.

PADAMOT - Palaeohydrogeological data analysis and model testing	
Start Date: 2001-11-01	**End Date**: 2004-11-01
Coordination: Nirex Ltd, United Kingdom	**Participating countries:** Czech Republic, Spain, Sweden and United Kingdom

New project

A new project with the acronyms "NET.EXCEL" is being negotiated with the European Commission. It has the objective of forming a network of end-users for discussing means and criteria for prioritising research projects with a broad European interest, and to make a list based upon these guidelines. The project work covers crystalline rock, salt and clay.

NET.EXCEL – Network of excellence in nuclear waste management and disposal	
Start Date: ?	**End Date**: 15 months duration
Coordination: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries:** Belgium, Finland, France, Germany, Spain, Sweden, Switzerland, and United Kingdom

References

Andersson P, Ludvigson J-E, Wass E, Holmqvist M, 2000a. TRUE block scale tracer test stage, interference tests, dilution tests and tracer tests, phase A, final draft report.
SKB IPR-00-28. Svensk Kärnbränslehantering AB.

Andersson P, Wass E, Holmqvist M, 2000b. True block scale tracer test stage, tracer tests phase B, first draft report.
SKB IPR-00-29. Svensk Kärnbränslehantering AB.

Byegård et al, 1999: LTDE Test Plan.
SKB IPR-99-36. Svensk Kärnbränslehantering AB.

Bäckblom G, Olsson O, 1994. Programme for tracer retention understanding experiments.
SKB PR 25-94-24. Svensk Kärnbränslehantering AB.

Elert M, 1999. Evaluation of modelling of the TRUE-1 radially converging and dipole tests with conservative tracers. The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Tasks 4C and 4D.
SKB TR-99-04. Svensk Kärnbränslehantering AB.

Elert M, Svensson H, 2001. Evaluation of modelling of the TRUE-1 radially converging tests with sorbing tracers.
SKB TR-01-12. Svensk Kärnbränslehantering AB.

Gustafson G, Ström A, 1995. The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Evaluation report on Task No 1, the LPT2 large scale field experiments.
SKB ICR 95-05. Svensk Kärnbränslehantering AB.

Gustafson G, Ström A, Vira J, 1997. The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Evaluation report on Task No 3, the Äspö tunnel drawdown experiment.
SKB ICR 97-06. Svensk Kärnbränslehantering AB.

Goudarzi R, Röshoff K, Feng Q, 2001. Sensor data report (Period: 000126-011101). Canister Retrieval Test. Report No: 3.
SKB IPR-02-04. Svensk Kärnbränslehantering AB.

Haggerty R, 1999. Application of the multirate diffusion approach in tracer test studies at Äspö HRL.
SKB R-99-62. Svensk Kärnbränslehantering AB.

Hermanson J, Doe T, 2000. TRUE Block Scale Project. March '00 structural and hydraulic model based on borehole data from KI0025F03.
SKB IPR-00-34. Svensk Kärnbränslehantering AB.

Jansson M, Eriksen T E, 2001. CHEMLAB – A probe for in-situ radionuclide experiments.
SKB TR 01-14. Svensk Kärnbränslehantering AB.

Jarsjö J, Destouni G, Gale J, 2001. Groundwater degassing and two-phase flow in fractured rock.
SKB TR-01-13. Svensk Kärnbränslehantering AB.

Karnland O, Sandén T, Johannesson L-E, Eriksen T, Jansson M, Wold S, Pedersen K, Motamedi M, Rosborg B, 2000. Long term test of buffer material. Final Report on the pilot parcels.
SKB TR-00-22. Svensk Kärnbränslehantering AB.

Kersting A B, Efured D W, Finnegan D L, Rokop D J, Smith D K, Thompson L J, 1999. Migration of plutonium in groundwater at the Nevada Test Site.
Nature, 297, 7 January, 56-59.

Laaksoharju M, Degueldre C l, Skårman C, 1995. Studies of colloids and their importance for repository performance assessment.
SKB TR 95-24. Svensk Kärnbränslehantering AB.

Pedersen K, 1999. Subterranean microorganisms and radioactive disposal in Sweden.
Engineering Geology 52, 163–176.

Rhén I, Gustafson G, Stanfors R, Wikberg P, 1997. Äspö HRL - Geoscientific evaluation 1997/5. Models based on site characterization 1986-1995
SKB TR 97-06. Svensk Kärnbränslehantering AB.

Smellie J (ed.), 2000. Status report on the Matris Fluid Experiment. June 1998-June 2000.
SKB IPR 00-35. Svensk Kärnbränslehantering AB.

Svensson U, 1997a. A regional analysis of groundwater flow and salinity distribution in the Äspö area.
SKB TR 97-09. Svensk Kärnbränslehantering AB.

Svensson U, 1997b. A site scale analysis of groundwater flow and salinity distribution in the Äspö area.
SKB TR 97-17. Svensk Kärnbränslehantering AB.

Svensson U, 1999a. A laboratory scale analysis of groundwater flow and salinity distribution in the Äspö area.
SKB TR 99-24. Svensk Kärnbränslehantering AB.

Svensson U, 1999b. Representation of fracture networks as grid cell conductivities.
SKB TR 99-25. Svensk Kärnbränslehantering AB.

SKB, 2000. Samlad redovisning av metod, platsval och program inför platsundersökningsskedet (In Swedish). December 2000.
Svensk Kärnbränslehantering AB.

SKB, 2001a. RD&D-Programme 2001. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste.
SKB TR-01-30. Svensk Kärnbränslehantering AB.

SKB, 2001b. First TRUE Stage - Transport of solutes in an interpreted single fracture. Proceedings from the 4th International Seminar Äspö, September 9-11, 2000.
SKB TR-01-24. Svensk Kärnbränslehantering AB.

Winberg A, 1997. Test plan for the TRUE Block Scale Experiment.
SKB ICR 97-01. Svensk Kärnbränslehantering AB.

Winberg A, Andersson P, Hermansson J, Byegård J, Cvetkovic V, Birgersson L, 2000. Final Report of the First TRUE Stage.
SKB TR-00-07. Svensk Kärnbränslehantering AB.