Technical Report

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Äspö Hard Rock Laboratory

Annual Report 2000

Svensk Kärnbränslehantering AB

June 2001

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Abstract

The Äspö Hard Rock Laboratory constitutes an important component of SKB's work to design, construct, and implement a deep geological repository for spent nuclear fuel and to develop and test methods for characterisation of selected repository sites.

The rock surrounding the repository constitutes a natural barrier to release of radionuclides from a deep repository. The retention effect of the rock has been studied by tracer tests in the Tracer Retention Understanding Experiments (TRUE) and the TRUE Block Scale (TRUE BS). These tests are supplemented by the new Long Term Diffusion Experiment (LTDE) . The experimental programme is designed to generate data for conceptual and numerical modelling at regular intervals. During year 2000 the field experiments of TRUE BS (50 m scale) were completed and preparations made for the LTDE (migration through a fracture wall and into the rock), including boring of approximately 10 m deep hole with 300 mm diameter. TRUE (5 m scale) completed earlier than year 2000 was finally reported.

Laboratory investigations have difficulties in simulating natural conditions and need supplementary field studies to support validation exercises. A special borehole probe, CHEMLAB, has therefore been designed for different kinds of validation experiments where data can be obtained representative for the in-situ properties of groundwater at repository depth. During 2000 migration experiments were made with actinides (Am, Np and Pu) in CHEMLAB 2, the simplified supplement to CHEMLAB 1.

Colloids of nuclides as well as of bentonite might affect the migration of released radionuclides and a separate project was planned during 2000 to assess the existance, stability and mobility of colloids.

The development of numerical modelling tools continues with the general objective to improve the numerical models in terms of flow and transport and to update the site-scale and laboratory scale models for the Äspö HRL. Modelling of groundwater flow and transport of solutes is made within a Task Force with eight of the international organisations represented. The Task 5 was completed during the year and the Task 6 planned for.

The Matrix Fluid Chemistry project aims at determining the origin and age of matrix fluids and the experiment has been designed to sample matrix fluids from predetermined, isolated borehole sections by specialised equipment. The water pressure has slowly raised in section 4 during the year, but not to a level where sampling can be made.

The Äspö HRL also has the task to demonstrate and perform full scale tests of the function of different components of the repository system, which are of importance for long-term safety. It is also important to show that high quality can be achieved in design, construction, and operation of a repository. Several experiments are in operation. The Prototype Repository experiment is focused on testing and demonstrating repository system function in full scale, and consists of six deposition holes with canisters and electric heaters surrounded by highly compacted bentonite. The tunnel is to be backfilled and plugged The work during 2000 has focused on geoscientific characterisation and specially hydraulic properties and conditions of the rock. Preparatory work with

design, purchase and manufacturing as well as rock work (slots for the two plugs) have been going on with the aim of preparing for start of installation during the second quarter of 2001. In September the contract with EC was signed for a period of 42 months.Equipment for installation of bentonite blocks and canisters were tested before start of installation in the Canister Retrieval Test. This test was completed in October and the heaters as well as the artificial saturation system was turned on immediately thereafter. The thermal load in the canister was set to 1700 W initially, which is the average load in the canisters in the future Swedish programmeme. After three months the load will be increased to 2600 W in order to obtain a temperature of 90°C on the surface of the single canister.

The objectives of the Demonstration of Repository Technology are to develop, test, and demonstrate methodology and equipment for encapsulation and deposition of spent nuclear fuel. The demonstration of handling and deposition is made with the specially designed full scale prototype to a deposition machine at 420 m level. This tunnel is also used as an exhibition hall for information about the Swedish Waste Management Programme.

The Backfill and Plug Test includes tests of backfill materials and emplacement methods and a test of a full-scale plug. Half the test part is filled with a mixture of 30% bentonite and crushed granite rock. The other half is filled with crushed rock without addition of bentonite, except for the upper 100–200 mm, where a slot was filled with blocks of highly compacted bentonite/crushed rock mixture and bentonite pellets. The backfill and rock has been instrumented with about 230 transducers for measuring the thermo-hydro-mechanical processes. Water saturation has been going on the whole year and the saturation speed has been slower than expected due to a lower salt content in the water than expected. In order to increase the speed a water with a higher salt content can be added and a higher water pressure applied. Still the saturation is expected to take the whole of year 2001 as well.

The Long Term Tests of Buffer Material (LOT) aims to validate models of buffer performance at standard KBS-3 repository conditions, and at quantifying clay buffer alteration processes at adverse conditions. In this context adverse conditions have reference to e.g. super saline ground water, high temperatures, high temperature gradient over the buffer, high pH and high potassium concentration in clay pore water. Further, related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport are also studied. On-going activities during year 2000 have been on-line readings of temperature, total pressure, water pressure and water content. Decommissioning of one out of five parcels is scheduled to take place in 2001.

The operation of the facility has worked properly and an extensive rock support programmeme has been carried through covering the whole tunnel. The information group's main goal is to create public acceptance for SKB in co-operation with other departments in SKB. This is achieved by giving information about SKB, the Äspö HRL and the SKB siting programmeme. The visitors are also given a tour of the Äspö HRL. During year 2000 12 760 visitors (12 211 during year 1999) came to the Äspö HRL. They have represented the general public, communities where SKB performs feasibility studies, teachers, students, politicians, journalists and visitors from foreign countries

One objective with the Äspö HRL is to test and develop techniques before they are applied at the candidate sites. In this context efficient techniques are required to handle, interpret and archive the huge amount of data collected during site characterisation. At present the SICADA data structure contains the sciences engineering, geology, geophysics, geotechnics, groundwater chemistry, hydrology, meteorology and rock mechanics. Data have successively been stored in SICADA during the year. On-line recording of groundwater changes (hydraulic and chemical) has been made by the installed Hydro Monitoring System (HMS). Groundwater sampling was performed once in boreholes drilled from the ground surface and from the underground tunnels. The analysis presented expected results.

Nine organisations from eight countries participated during 2000 in the Äspö HRL research in addition to SKB.

Sammanfattning

Äspölaboratoriet utgör en betydelsefull del av SKB:s arbete med utformning, bygge och drift av ett djupförvar för använt kärnbränsle samt för utveckling och testning av metoder för karakterisering och val av förvarsplats.

Bergmassan som omger ett förvar utgör en naturlig barriär mot radionuklider från ett djupförvar. Bergmassan förmåga att fördröja transporten har studerats med hjälp av spårämnesförsök i Tracer Retention Understanding Experiments (TRUE) och TRUE Block Scale (TRUE BS). Dessa försök kompletteras med det nya Long Term Diffusion Experiment (LTDE). Försöksprogrammet är utformat för att ta fram data till regelbunden konceptuell och matematisk modellering. Under år 2000 avlutades experimenten i TRUE BS (50 m skala) samt förbereddes LTDE-försök (transport genom en sprickas bergvägg och in i bergmassan), inkluderande borrning av ett nära 10 m djupt hål med diametern 300 mm. TRUE (5 m skala), som avslutades före år 2000, slutrapporterades.

Laboratoriestudier har svårt att simulera naturliga förhållanden och behöver kompletteras med fältstudier för att stödja valideringsstudier. En speciell borrhålsutrustning, CHEMLAB, har därför utformats för olika slag av valideringsexperiment, där data kan erhållas som är representativa för in situ-förhållande i grundvatten på förvarsdjup. Under år 2000 har transportexperiment gjorts med aktinider (Am, Np och Pu) i CHEMLAB 2, den förenklade kompletteringen till CHEMLAB 1.

Kolloider av nuklider liksom av bentonit kan påverka transporten av frigjorda radionuklider och ett separat projekt planerades under år 2000 för analys av förekomst, stabilitet och rörlighet hos kolloider.

Utvecklingen av matematisk modelleringsverktyg fortsätter med det allmänna syftet att förbättra de numeriska modellerna i fråga om flöde och transport samt att uppdatera modellerna i plats-skala och laboratorieskala för Äspö HRL. Modellering av grundvattenflöde och transport av lösta ämnen görs i en Task Force med åtta deltagande, internationella organisationer. Task 5 avslutades under 2000 och Task 6 planerades.

Projektet Matrix Fluid Chemistry syftar till att bestämma ursprung och ålder hos matrisvatten, och experimentet has utformats i syfte att provta matrisvatten från förutbestämda, isolerade borrhålssektioner med hjälp av specialinstrument. Vattentrycket har under året sakta stigit i sektion 4 men inte till en sådan nivå att provtagning är möjlig.

Äspö HRL har också till uppgift att demonstrera och genomföra fullskaleexperiment på olika förvarskomponenters funktion, vilka är viktiga för den långsiktiga säkerheten. Det är också viktigt att visa att en hög kvalitet kan uppnås i utformning, byggande och drift av ett djupförvar. Flera experiment pågår.

Prototypförvaret fokuseras på test och demonstration av förvarskomponenters funktion i fullstor skala och består av sex deponeringshål med kapslar och elektriska värmare omgivna av högkompakterad bentonit. Tunneln återfylls och pluggas igen. Arbetet under 2000 har koncentrerats på geovetenskaplig karakterisering av bergmassan, speciellt dess geohydrauliska egenskaper och förhållanden. Förberedande arbete med utformning, upphandling och tillverkning liksom bergarbeten (slits till de två pluggarna) har pågått med målet att förbereda för installationsstart under andra kvartalet 2001. I september skrevs kontraktet med EU under gällande en period på 42 månader.

Utrustning för installation av bentonitblock och kapslar testades innan installationen av Canister Retrieval Test startade. Denna installation var klar i oktober då också värmarna och det artificiella bevätningssystemet slogs på. Den termiska lasten i kapsel sattes från början in på 1700 W, vilket är den beräknade, genomsnittliga effekten i varje kapsel i det framtida djupförvaret. Efter tre månader ska effekten höjas till 2600 W så att temperaturen blir 90°C på ytan av den ensamma kapseln.

Syftet med Demonstration of Repository Technology är att utveckla, testa och demonstrera metod och utrustning för inkapsling och deponering av använt kärnbränsle. Demonstration av hantering och deponering görs med den specialbyggda fullskaleprototypen till deponeringsmaskin på 420 m nivå. Nivån används också som besökshall för information om det svenska avfallsprogrammet.

Backfill and Plug Test inkluderar tester av återfyllnadsmaterial och inplaceringsmetoder samt test av en fullskaleplugg. Halva experimentet är fyllt med en blandning av 30% bentonit och 70% krossat berg. Den andra halvan är fylld med krossat berg utan bentonittillskott förutom i taket där ett 100–200 mm tjockt lager byggts upp av högkompakterade block av bentonit och krossat berg samt bentonitpellets. Återfyllen och berget har försetts med 230 mätinstrument för termo-hydro-mekaniska processer. Vattenmättnad har pågått hela året och mättnadshastigheten har varit långsammare än beräknat till följd av lägre salthalt i grundvattnet än förväntat. För att öka på vattenmättnadshastigheten kan salthalten i det tillsatta vattnet ökas och ett högre vattentryck läggas på. Ändå tar bevätningen hela år 2001.

Long Term Tests of Buffer Material (LOT) syftar till validering av modeller för buffertens funktion under normala KBS-3-förhållanden samt till kvantifiering av omvandlingsprocesser i bufferten under onormala förhållanden. I detta sammanhang betyder onormala förhållanden hög salthalt i grundvattnet, hög temperatur, hög temperaturgradient över bufferten, högt pH och hög kaliumkoncentration i bentonitlerans porer. Processer rörande mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport studeras också. Pågående aktiviteter under 2000 har varit kontinuerlig avläsning av givare för temperatur, totalt tryck, vattentryck och vatteninnehåll. Rivning av ett av fem paket görs under 2001.

Driften av Äspöanläggningen har flutit på programenligt och ett omfattande bergförstärkningsprogram har genomförts i hela tunneln. Informationsgruppens huvudsakliga mål är att i samarbete med andra avdelningar inom SKB skapa acceptans hos allmänheten för SKB. Detta sker genom information om företaget, Äspö HRL och SKB:s platsvalsprogram. Besökare guidas också under jord. Under år 2000 besökte 12 760 personer Äspö (12 211 under 1999). De representerade allmänheten, kommuner där SKB bedriver förstudier, lärare, politiker, journalister och andra länder.

Ett syfte med Äspö HRL är att test och utveckla teknik innan den kommer till användning på kandidatplatserna. I detta sammanhang är effektiv teknik nödvändig för att hantera, tolka och arkivera stora mängder data som samlas in under platskarakteriseringen. För närvarande innehåller SICADA datastruktur för ingenjörsvetenskap, geologi, geofysik, geoteknik, grundvattenkemi, hydrologi, metrologi och bergmekanik. Data har kontinuerligt lagrats i SICADA under året. Kontinuerlig registrering av grundvattenförändringar (hydrauliska och kemiska) har gjorts av Hydro Monitoring System (HMS). Grundvattenprovtagning har skett en gång i borrhål från dagen och från under jord. Analysresultaten redovisade förväntade värden.

Nio organisationer från åtta länder deltog under 2000 i Äspö HRL:s forskning förutom SKB.

Content

1 General

1.1 Background

The Äspö Hard Rock Laboratory constitutes an important component of SKB's work to design and construct a deep geological repository for spent fuel and to develop and test methods for characterisation of selected repository site. The role of the Äspö Hard Rock Laboratory is to provide input to the performance assessments that have to be supplied as part of each license application and to develop, test, and evaluate methods for site investigations, detailed investigations, repository construction as well as disposal and backfilling of tunnels before they are applied within the deep repository programme. The Äspö HRL should also provide experience and train staff in performing the various tasks within the deep repository programme. Äspö HRL also offers the opportunity to test various aspects of repository performance during a long time, up to 20 years, and will hence provide valuable input to the evaluation made in conjunction with application for regular operation of the deep repository.

In 1986 SKB decided to construct the underground rock laboratory in order to provide an opportunity for research, development, and demonstration in a realistic and undisturbed underground rock environment down to the depth planned for a future deep repository. In the autumn of 1986, SKB initiated field work for the siting of the underground laboratory in the Simpevarp area in the municipality of Oskarshamn (Figure 1-1), and focused the work at the end of 1988 to the southern Äspö about 2 km north of the Oskarshamn power station. Excavation started on October 1st, 1990 after approval had been obtained from the authorities concerned, and was completed in February 1995.

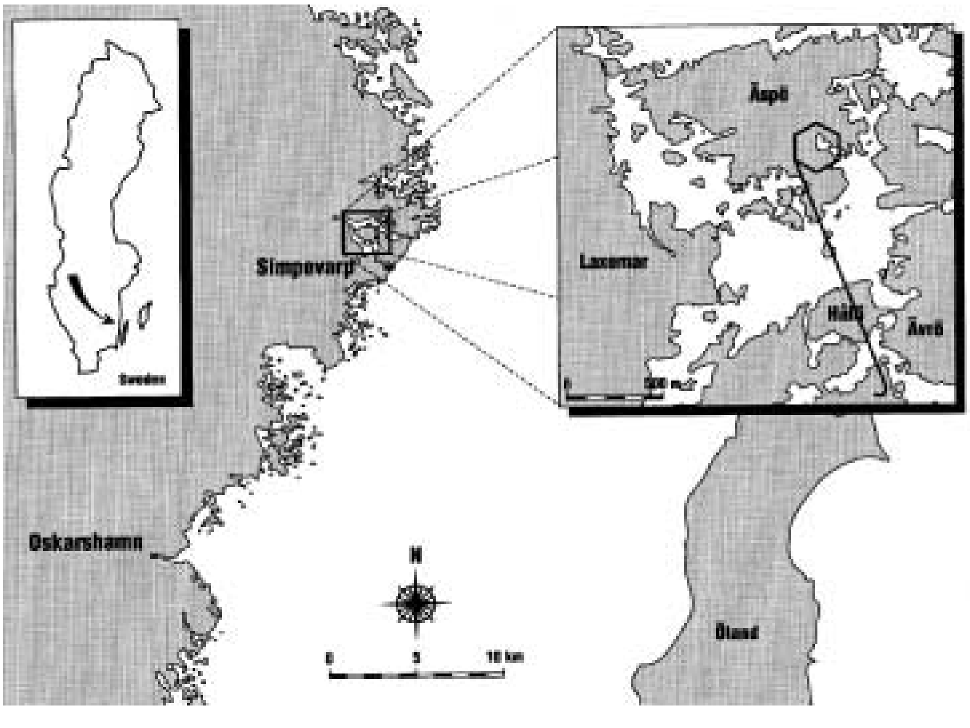


Figure 1-1. *Location of the Äspö HRL.*

The Äspö HRL has been designed to meet the needs of the research, development, and demonstration projects that are planned for the Operating Phase. 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 (Figure 1-2). 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 techniques. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts. Äspö Research Village is located at the surface on the Äspö Island and it comprises office facilities, storage facilities, and machinery for hoist and ventilation (Figure 1-3).

The work with the Äspö HRL has been divided into three phases: the pre-investigation phase, the construction phase, and the operating 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 operating 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 **Operating phase began in 1995**. A preliminary outline of the programme for the Operating phase was given in SKB's Research, Development and Demonstration (RD&D) Program 1992. Since then the programme has been revised and the basis for the current programme is described in SKB's RD&D Program 1998.

Figure 1-2. *Overview of the Äspö Hard Rock Laboratory Facilities.*

Figure 1-3. *Overview of the Äspö Research Village.*

1.2 Goals

SKB decided to construct the Äspö HRL for the main purpose of providing an opportunity for research, development and demonstration in a realistic and undisturbed underground rock environment down to the depth planned for the future deep repository. Important tasks for the Äspö HRL are:

- to increase scientific understanding of the safety margins of the deep repository,
- to test and verify technology that provide cost reductions and simplifies the repository concept without compromising safety,
- to demonstrate technology that will be used in the deep repository,
- to provide experience and training of staff, and
- to inform about technology and methods to be used in the deep repository.

To meet the overall time schedule for SKB's RD&D work, the following stage goals have been defined for the work at the Äspö Hard Rock Laboratory.

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

2 **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 function of the host rock**
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 a full scale different components of importance for the long-term safety of a deep repository system and to show that high quality can be achieved in design, construction, and operation of system components.

1.3 Organisation

1.3.1 Repository Technology and the Äspö HRL

The Äspö HRL and the associated research, development, and demonstration tasks are managed by the Director of Repository Technology (Olle Olsson). The International Cooperation at the Äspö Hard Rock Laboratory is the responsibility of the Director of Repository Technology, Olle Olsson, and SKB's International Coordinator, Monica Hammarström.

The Repository Technology unit is part of the Safety and Technology division that is responsible for technical development of the repository system, research, and safety assessments (Figure 1-4).

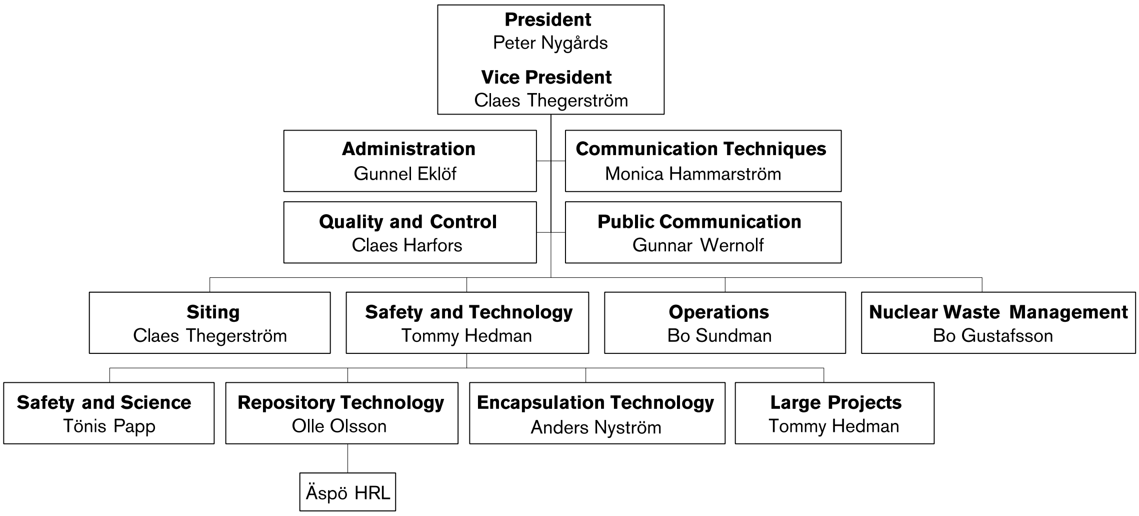


Figure 1-4. *Organisation chart for SKB.*

The Repository Technology unit is organised as a matrix organisation with three Senior Project Managers with responsibility to define the programme and manage the projects within their respective areas of responsibility (Figure 1-5). The three main tasks are:

- Site investigations with responsibility to provide an appropriate site investigation programme, methods, equipment, and a competent organisation for site and detailed investigations to be applied when needed.
- Repository technology with responsibility for development, testing, planning, design, and demonstration of the technology and the methods needed to construct a deep repository.
- Natural barriers with responsibility for management and performance of research projects at the Äspö HRL aimed at resolving issues concerning the function of the natural barrier.

The Senior Project Managers report directly to the Director of Repository Technology.

The staff is organised into the following groups:

- The Technology and Science group is responsible for maintaining knowledge about the characterisation and experimental methods that have been used and the results that have been obtained from work at Äspö. The group is also responsible for the successive updates of the geoscientific models of Äspö based on new data from the experiments.
- The Experiment Service group is responsible for the co-ordination of projects undertaken at the Äspö HRL and providing service (design, installations, measurements etc) to the experiments undertaken at Äspö HRL. They are also responsible for operation and maintenance of monitoring systems and experimental equipment at Äspö.

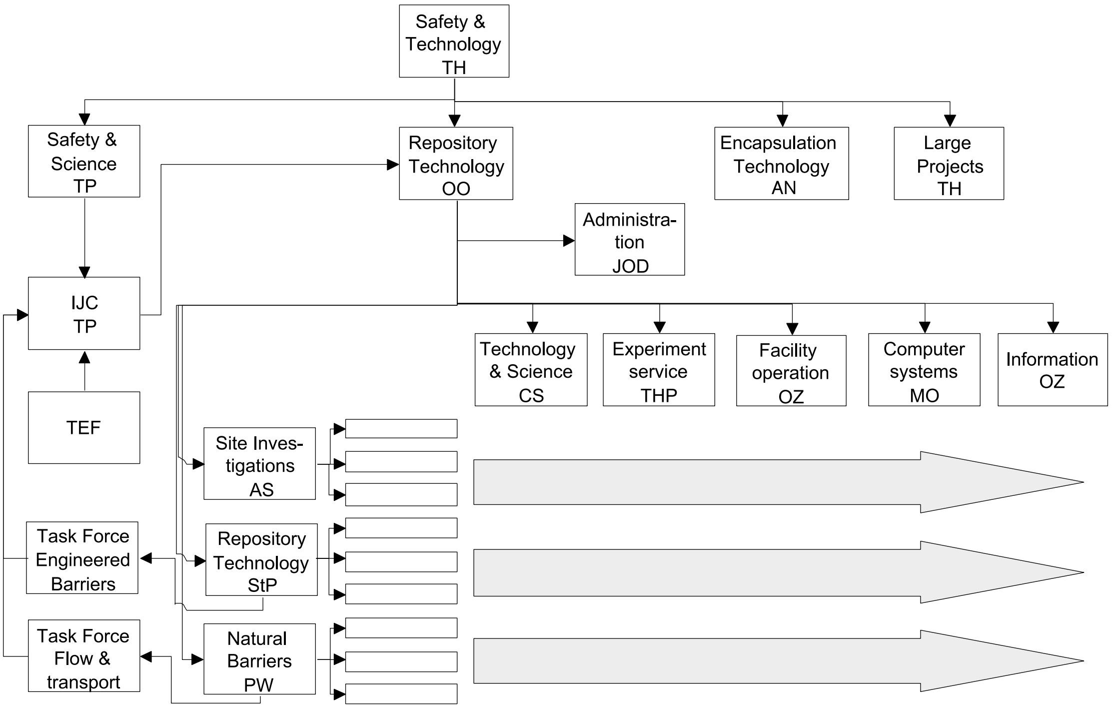


Figure 1-5. Organisation of Repository Technology.

- The Computer Systems group is responsible for operation and maintenance of computer hardware at SKB's offices in Oskarshamn. They are also responsible for the further development and administration of SKB's geoscientific database, SICADA, and the Rock Visualisation System (RVS).
- The Facility Operations group is responsible for operation and maintenance of the Äspö HRL offices, workshops and underground facilities.
- The Information group is responsible for arranging visits to SKB's facilities and providing information to visitors to Äspö HRL and SKB's other facilities in Oskarshamn.
- The Administration group is responsible for providing administrative service and quality systems.

Each major research and development task is organised as a project that is led by a Project Manger who reports to one of the Senior Project Managers. Each Project Manager will be assisted by an On-Site Co-ordinator from the Äspö HRL 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. As of December 2000 nine foreign organisations are participating in the Äspö HRL in addition to SKB. These organisations are: Japan Nuclear Cycle Development Institute (JNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI), Japan; Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA), France; POSIVA Oy, Finland; United Kingdom Nirex Limited, NIREX, Great Britain; Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA), Switzerland; Bundesministerium für Wirtschaft und Technologie (BMWi), Germany; Empresa Nacional de Residuos Radiactivos (ENRESA), Spain, and United States Department of Energy, Carlsbad Field Office (USDOE/CBFO).

1.3.3 Advisory Groups

The international partners and SKB reached a joint decision to form the Äspö International Joint Committee (IJC) to be convened in connection with Technical Evaluation Forum (TEF) meetings. The role of the IJC is to co-ordinate the contributions of organisations participating in the Äspö HRL. The TEF meetings are organised to facilitate a broad scientific discussion and review of results obtained and planned work. Technical experts from each participating organisation and the IJC delegates participate in the TEF meetings. Chairman of IJC/TEF is Tönis Papp and secretary is Monica Hammarström (during 2000).

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.

1.3.4 Task Force on modelling of groundwater flow and transport of solutes

The Technical Co-ordinating Board (TCB) which preceded the IJC established the Task Force on modelling of groundwater flow and transport of solutes. The Task Force reviews and or proposes detailed experimental and analytical approaches for investigations and experiments at Äspö HRL. The group convenes twice a year. Approximately ten different modelling groups are now actively involved in the work. Chairman (December 2000) is Gunnar Gustafson, CTH and secretary is Mansueto Morosini, SKB.

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 experimental sites be allocated so that interference between different experiments is minimised. The current allocation of experimental sites within the Äspö HRL is shown in Figure 1-6.

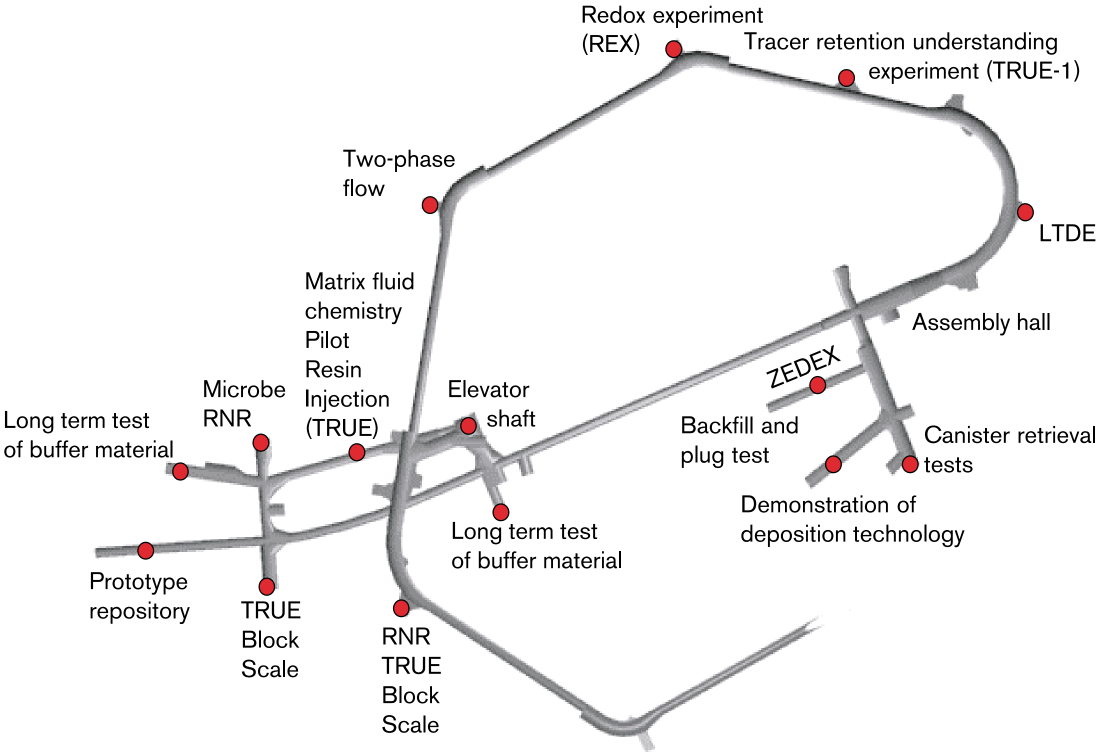


Figure 1-6. *Underground excavations at the 300–450 m levels and current allocation of experimental sites.*

2 Methodology for detailed characterisation of rock underground

2.1 General

A programme for detailed characterisation will be devised before detailed characterisation is initiated on a selected site and construction of the surface and underground portions of the deep repository is commenced. In conjunction with the excavationof the Äspö tunnel, several different investigation methods have been tested and the usefulness of these methods for detailed characterisation for a deep repository is being evaluated. Preliminary experience from Äspö shows that there is a need for refinement of these methods to enhance the quality of collected data, boost efficiency and improve reliability in a demanding underground environment. Furthermore, the detailed characterisation programme needs to be designed so that good co-ordination is obtained between rock investigations and construction activities.

The objectives are:

- to test existing and new methods to clarify their usefulness for detailed characterisation. The methods to be tested are chosen on the basis of their potential use within the detailed characterisation programme,
- to refine important methods in a detailed characterisation programme to enhance data quality, efficiency and reliability.

Detailed characterisation will facilitate refinement of site models originally based on data from the ground surface and surface boreholes. The refined models will provide the basis for updating the layout of the repository and adapting it to local conditions. Due to the heterogeneity of the rock, the layout of the repository needs to be adapted to the gradually refined model of rock conditions. This approach has a long tradition in underground construction and it should be used also for a deep repository.

2.2 Underground measurement methods and methodology

2.2.1 Background

Detailed investigation for SKB's deep repository will include a characterisation step involving one candidate site, subsequent following the site investigation which is expected to be carried out on at least two sites (SKB has proposed investigation of the rock in three municipalities representing three different geologic settings – municipalities' and government's decisions are scheduled for year 2001). Detailed investigations will mostly concern investigations from the underground.

During the Construction phase of the Äspö HRL documentation, measurements and testing activities from underground were performed. Other underground investigation methods have been used, and will further on be used, during the Operational phase. Preliminary experience shows that methods and instruments in some cases have to be improved, with regard to correctness in data, efficiency and robustness.

2.2.2 Objectives

The aim is to evaluate the feasibility and usefulness of the methods used, define areas, methods and instruments where improvements have to be made. The work also includes testing of other methods (mainly commercially available) which have not been used before. Tests of methods for detailed characterisation are mainly intended to be carried out within the framework of ongoing projects.

2.2.3 Results

An evaluation of MWD (Measurement While Drilling) used during drilling of 2 855 metres of percussion probe holes during the excavation of the Äspö HRL tunnel has been performed. During drilling of 20 m long probe holes on either side of the tunnel a logging instrument from Bever Control A/S was used. Rate of penetration, feed pressure, rotational pressure and percussion pressure were monitored every 10th centimetre. An evaluation of the data has been performed and presented like hardness and fracturing of the rock. The result is that the hardness can be evaluated relatively good, the fracturing needs denser data sampling like one point per centimetre which is possible with the technique used today. Today it is also possible to monitor water flow and water pressure which can give information of the waterbearing features in the rock.

2.2.4 Planned Work

A report on underground investigation methods used during the construction phase of the Äspö HRL will be published around mid 2001. The report will describe the different methods used with regard to instrument or other working tools and measurement methodology. Resolution and accuracy of the measured values as well as general aspects of errors will be discussed. The evaluation part will address the usefulness and feasibility of the methods. Recommendations on possible modifications will also be given.

Based on the report, but also on the basis of other project evaluation and validation reports, further testing of existing methods and testing of new methods will be planned.

2.3 Rock Visualisation System

2.3.1 Background

A digital three dimensional site descriptive model is built by successive collection, processing and interpretation of site data. All site data will be stored in SICADA (SKB's Site Characterisation Database). Furthermore all geological and geophysical maps will be available in SKB's GIS database. Advanced software applications are needed to create the site descriptive model based on correct and documented sets of investigation data.

2.3.2 Objectives

The experiences obtained from SKB's site investigations and at Äspö HRL have shown that it is very important to have the possibility to test interactively in 3D different possible connections between observations in boreholes, tunnels and on the ground surface. By effectively visualising the model, based on available site data in SICADA, it is also possible to optimise new investigation efforts. Finally, during the design of the Deep Repository, the site descriptive model, also used as a basis in the safety assessment, will be the basis for adaptation of the tunnel layout to the different rock characteristics at the site.

To fulfil the above strategy and requirements SKB are developing the Rock Visualisation System. The Principal Investigators in the Äspö project and other geoscientific experts in SKB's organisation have been involved in defining the functions needed in the system.

2.3.3 System concept

SKB's Rock Visualisation System is based on the CAD-system MicroStation/J. It is designed as a single-user system, but the data exchange link between RVS and SKB's Site Characterisation Database System (SICADA) is based on a client/server technique. There is also a database engine (MS/Access 97) required on each RVS workstation. An open architecture based on the ODBC data exchange concept is used. Hence, by using ODBC, it will be easy to replace MS/Access 97 if another database is needed in the future.

In the Rock Visualisation System, in contrast to standard MicroStation, the work is not based on design files (drawing files) and levels but on projects and objects. In order to work in an organised matter, and for practical reasons, it is for *larger projects* highly recommended to separate the visualisation work into three sub-projects:

- Data project (containing visualisations of background data).
- Model project (containing modelled objects).
- Construction project (containing underground constructions).

Hence, data, model and construction can be handled separately which is a great advantage, mainly regarding version handling, when data are updated continuously and much more often than the model. The data project is normally attached as a background project to the model project. In the same way the model project is used as a background project when working with underground construction tasks.

For *small projects*, limited in time and extension, it could, however, be more efficient to gather all information in one project, but independent of how the total set of objects are managed they can be mixed arbitrary when displayed on the screen. An example is shown in Figure 2-1. By using the *object list*, an unique feature in the system, objects can be turned on (visible) or off (not visible).

From the users point of view the system can be divided in four main parts, namely:

- Data visualisation (mainly borehole data).
- Modelling.
- Construction.
- Drawing.

An overview description of each part has been presented in the Annual Report for 1997.

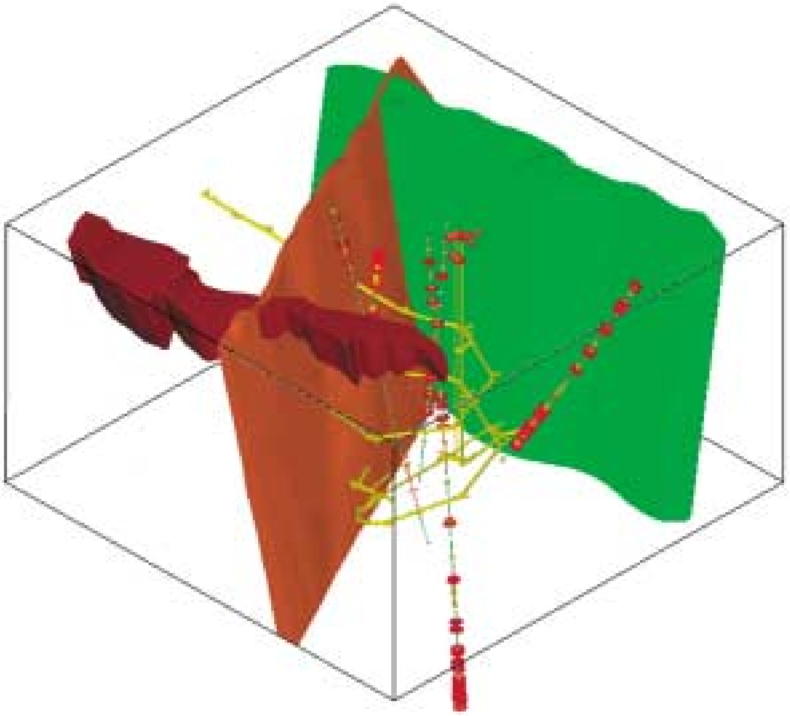


Figure 2-1. *Objects can be turned on (visible) or off (not visible), by using the* ***object selector****. The model volume visualised in this case includes visible objects of several types including borehole data, modelled objects (a fracture zone in brown and two rock bodies in red and green) and construction objects (tunnels in yellow).*

2.3.4 Results

RVS version 2.1 and 2.2 has been released during 2000. The programming of version 2.3 was completed in December 2000. Totally more than 30 new or improved existing functions have been produced. Some of these functions are described briefly in the following text.

The unique *Object List* has been improved. As a result it will be easier to have an overview of all active objects in a model or set of visualisations. As an example all borehole visualisations are stored as sub-objects to the borehole it self. A new column, named *user*, has also been inserted in the Object List. This column stores the name of the person who has created a certain object in the model. Some other columns in the list have been renamed in order to be more understandable.

The new feature *Work set* has been introduced to make it possible for the user to reduce the amount of borehole data in the local database. As an additional positive effect the number of boreholes in some lists are shortened as wanted.

In the previous version a discontinuity surface, describing a single fracture plane, was automatically extended to the borders of the modelled rock volume. This restriction has been removed. *A discontinuity is now extended by rules given by the user*. It is also possible to *remodel discontinuities*.

Earlier imported *DGN-files can now be reloaded* if they have been updated in standard MicroStation/J during the modelling process.

At some site investigation areas a *set of co-ordinate systems* have been used. Even this circumstance is supported by the latest version (2.3) of RVS. This improvement required lot of effort and time but resulted in useful modifications in the data structure of SICADA.

By using the software AuthorIT the *on-line help* have been refined. AuthorIT helps the administrator to manage the complete set of information needed in a User's manual. When the help information have been set up and configured, it is easy to produce HTML-documents, to be executed from any dialogue window in the RVS application, or printed documents.

A review study project has been carried out. The aim with this project was to have an independent opinion of the capabilities, but even lack of capabilities, available in the Rock Visualisation System. The study done by Dr Matthew White and Dr Andy Lind at ENVIROSQUANTISCI in England will be an important basis when planning for further developments of SKB's Rock Visualisation System. In the final report a set of recommendations have been presented.

3 Test of models for description of the barrier function of the host rock

3.1 General

The Natural Barriers of a repository for spent nuclear fuel is the bedrock surrounding the engineered barriers. The barrier functions considered when assessing the long term safety are *isolation*, *retention* and *dilution*. These functions are provided by the very existence of the bedrock, its properties and the on-going processes in the rock. The goal of the experiments within Natural Barriers is to increase the scientific knowledge of the safety margins of the deep repository and to provide data for performance and safety assessment calculations. The priority for the on-going experiments on the natural barriers is to concentrate the efforts on those experiments which results are needed for the planning of the site investigations, planned to start in 2002.

Isolation is the prime function of the repository. It is obtained through the co-function of the engineered and the natural barriers. In the KBS-3 disposal concept the copper canister is expected to remain unbroken for millions of years, in case it is intact at deposition. The bentonite clay barrier will further protect the copper canister mechanically against displacements across the deposition hole as well as chemically against transport of possible corrodants to the canister by minimising the flow of water to the canister. For other waste types, not insulated by copper, the flow of water to the canister/waste containment is largely determining the magnitude at which the corrosion 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. Present day hydrochemistry is favourable for a low corrosion rate of the canister. These conditions can be expected to persist up to, at least, the next major glaciation. The host rock should provide mechanical protection for the engineered barriers and future rock movements should not jeopardise the integrity of the engineered barriers. This can be achieved by proper repository design and emplacement of spent fuel away from active faults.

Conceptual and numerical groundwater flow models have been developed through the entire Äspö project up to now. Further development of the tools for groundwater flow and transport calculations is made to meet the needs of the site characterisation phase.

Hydrochemical stability has been assessed for both present day as well as previous conditions. The aim has been to explain possible chemical conditions in a repository host rock based on assumption of different climate conditions in the future. On-going projects aim at investigating the chemistry of the water in the pores of the rock matrix, and at understanding the microbial effects on the groundwater chemistry.

The *retention* of radionuclides dissolved in groundwater is the second most important barrier function of the repository. Retention will be provided by any system and process that interacts with the nuclides dissolved in the groundwater when eventually the water has come in contact with the waste form and dissolved radionuclides. Retention is provided by the physical and chemical processes, which occur in the nearfield and farfield.

Some elements are strongly retarded while the non-sorbing nuclides are migrating with the speed of the flowing groundwater. The major emphasis in the safety assessment calculations has been on the weakly retarded nuclides because these can potentially be transported up to the biosphere.

The large amount of activity in a repository is caused by the fission products, Cs, Sr, I, Tc, and the transuranic elements Am, Np, and Pu. The transuranics, Cs, and Tc are, if dissolved, effectively sorbed in the near field. However, in case neptunium and technetium are oxidized to neptonyl and pertechnetate by radiolyses from the waste they might be transported into the bentonite buffer before they are reduced to the insoluble tetravalent state.

Strontium and all negatively charged elements will be transported through the bentonite buffer by diffusion. They will then be retarded by the interaction with the fracture minerals in the flow paths of the rock and through the diffusion into the rock matrix. The effective retention of these nuclides is a combination of radioactive decay, sorption and diffusion. The more long-lived and the weaker the sorption of the nuclide, the more important is the actual groundwater flow for the migration. The chemical composition of the groundwater is important for the magnitude of sorption for some of the nuclides. Negatively charged nuclides are retarded from the groundwater flow only through the diffusion into the stagnant pores of the rock matrix.

Tracer tests are carried out within experiments in the TRUE projects. These are conducted at different scales with the aim of identifying detailed scale (5 m) and block scale (50 m) flow paths, retention of weakly and moderately sorbing tracers and the effect of matrix diffusion. In 2000 the experimental part of TRUE Block Scale was completed and the Long Term Diffusion Experiment (LTDE) was initiated. Modelling of the experiments is done by several groups associated to the Äspö Task Force for modelling of groundwater flow and transport of solutes.

Colloids might affect the retention of radionuclides. A separate project was planned during 2000 to assess the existence, stability and mobility of colloids.

CHEMLAB experiments are conducted with the moderately and highly sorbing nuclides. Experiments are carried out in simulated near field conditions (bentonite) and in tiny rock fractures. During 2001 experiments including effects of radiolysis will be carried out in the CHEMLAB 1 unit. In the CHEMLAB 2 unit experiments with actinides will be started.

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, and for performance assessment calculations on the conceptualisation of the flow. In the geosphere the dilution is caused by the dispersion in the groundwater flow.

No specific experiment is focussing on dilution. However, this process is included in a proposal for the next-coming modelling task within the Äspö Task Force for groundwater flow and transport of solutes.

3.2 Numerical Modelling

3.2.1 Background

Mathematical model 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 and at Äspö HRL several modelling concepts as Stochastic Continuum (SC), Discrete Fracture Network (DFN) and Channel Network (CN) have been used. SC approach has been used for the regional and site scale models /Svensson, 1997a,b/ and in the laboratory scale model the starting point has been a fracture network for assigning hydraulic properties to a SC model /Svensson, 1999a/. The methodology of how to transform the fracture network to the SC was shown in Svensson /1999b/. This is called the GEHYCO concept. Based on the new data available since the Äspö model 1996, reported in Rhén et al /1997b/, and the new concept of generating the conductivity field /Svensson, 1999b/, it is planned to update the site, laboratory and (possibly) the regional models of the Äspö area.

Tests of embedded grids have been made with the PHOENICS code. The purpose was to see if it was feasible to generate local dense grids to get high resolution and better possibilities to define small features in the model. The technique is expected to be useful for regional, site and laboratory scale models. Both the non-uniform and BFC (Body Fitted Co-ordinates) grids generates cells with high aspect ratio, i.e. $\Delta_x/\Delta_y >> 1$, which is a disadvantage when spatial assignment method for hydraulic conductivity is chosen. The advantage with embedded grid is that the cells are cubic which is considered better base for choosing spatial assignment method.

3.2.2 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 metres 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 Visualisation System (RVS) to the numerical code for groundwater flow and to export modelling results to the RVS.
- Increase the details in the models based on new knowledge of the Äspö site collected during the last years.

3.2.3 Modelling concept

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 development is deemed needed of both the codes 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 until year 2000 is PHOENICS, which has been used in regional scale, sites cale and laboratory models /Svensson, 1997a,b, 1999a/. A new code is under devepment by SKB which will be tested during 2001.

The results from the construction phase of the Äspö HRL showed a relatively high number of events with a high inflow rate during drilling. Features with a high transmissivity were drilled through at a number of times and these features were in several cases not a part of the deterministically defined major discontinuities. This has also been seen in boreholes made in the operation phase of the Äspö HRL. These features were called High Permeability Feature (HPF). The spatial distribution of these features, and features with lower transmissivity, has been studied and is a basis for modifying the modelling concepts /Rhén and Forsmark, 1999; Rhén et al, 1997b/.

High Permeability Feature (HPF), as defined in Rhén and Forsmark /1999/ consists of a fracture, system of fractures, or a fracture zone with an inflow rate (observed during drilling or flow logging) which exceeds 100 l/min or alternatively show a transmissivity $T \geq 10^{-5}$ m^2/s. Some of the conclusions from the study of the data from the pre-investigation and the construction phase of the Äspö HRL are presented in Rhén and Forsmark /1999/.

3.2.4 Results

The different modelling concepts have their benefits and drawbacks. It seems that SC approach may be most useful for the larger scales and the DFN approach has benefits in the smaller scale. The use of the SC approach demands that spatial correlation models can be established. The use of conventional geo-statistical methods has indicated problems when tests from boreholes have been used. These methods do not take into account the support scale in proper manner and the long distances between boreholes are a problem when a 3D-correlation structure is to be established. It was also stressed in Rhén et al /1997a/ the need to develop better spatial correlation models useful for the SC approach. One way of doing this is to incorporate geometrical models of the fracture network for the generation of the correlation model or directly create the conductivity field in a SC model. The first approach has been used by Hoch et al /1998/ and the second approach has been used by Svensson /1999a/. Important data for the test of the model in Svensson /1999a/ is the statistics of hydraulic conductivity based on the injection tests made with 3 m packer spacing but also the statistics of the distances between conductive features exceeding a specified limit of the transmissivity. The last type of statistics was for Äspö data presented in Rhén et al /1997b/ and later the analysis was updated with more data but focussed on High Permeability Features (HPF) /Rhén and Forsmark, 1999/. Both the results from Hoch et al /1998/ and Svensson /1999a,b/ seem promising in terms of the possibilities of generation anisotropic conditions as well as a more realistic correlation structure in the SC models. A more advanced way of performing a geo-statistical analysis also indicate good correspondence between statistical model based on the injection tests made with 3 m packer spacing and the conductivity field in the laboratory model /Painter, 1999; Svensson, 1999a/.

Partrack

Transport properties were only briefly studied during the pre-investigation and construction phase of Äspö HRL. During the operation phase much more effort is paid to increase the knowledge of the transport properties in fracture crystalline rock. Some of the results concerning transport properties in fracture crystalline rock was compiled in Rhén et al /1997b/ and was also used in the modelling /Svensson, 1997b/. These relations are approximate and uncertain but still considered useful for assigning properties to the rock mass on a large scale. More relevant transport data are available from mainly the TRUE project (Winberg, /1996/ and later reports from the project). Tests of modelling concepts for transport in SC have also been made. In Svensson /1992, 1994/ it was tested how micro-dispersion and sorption could be incorporated into a particle tracking routine. It was further developed and tested. The recent development is focused on description of physical and chemical processes. The basic idea in PARTRACK is that a particle can have two states "moving" or "non-moving". A frequency pair determines the rates by which a particle should change state. Obviously it is possible to describe sorption in this way but it has also been demonstrated that Taylor dispersion can be exactly parameterised by the two states. Up to now it has, however, not been possible to handle more than one process that causes dispersion. The recent development allows for several physical and chemical processes working in parallel. It is thus possible to simulate the movement of a particle that is exposed to, for example Taylor dispersion when moving in the flow, diffusion into a stagnant pool, sorption on the walls of that pool and perhaps even diffusion into the rock matrix. The recent development of PARTRACK is employing some concepts and formulations from the Multi-rate model of diffusion (Haggerty and Gorelick /1995/ and also the applications of McKenna /1999/). Presently the mathematical derivations, software development and some basic tests have been carried out. It can be expected that future work should be directed towards implementation of relevant physical and chemical processes.

Transport of a tracer travelling through a fracture network leads to dispersion for (at least) the following reasons as presented (see also Figure 3-1):

- **Intersections.** At a fracture intersection a tracer cloud may split up and enter pathways with different lengths and fluid velocities. This type of dispersion is often called macro-dispersion.
- **Channelling.** Spreading occurs within each fracture plane as the different streamlines have different path lengths and velocities. The flow channels may also merge or split up.
- **Taylor dispersion.** A velocity profile exists between the two bounding walls of the fracture. The resulting dispersion effect is called shear or Taylor dispersion.
- **Matrix diffusion and sorption.** Interaction with the rock, stagnant pools and microfissures causes a number of processes that in fact lead to a delay and dispersion of a tracer pulse. These include: sorption on the fracture walls, diffusion into the rock matrix with sorption on inner surfaces and interaction with gouge.

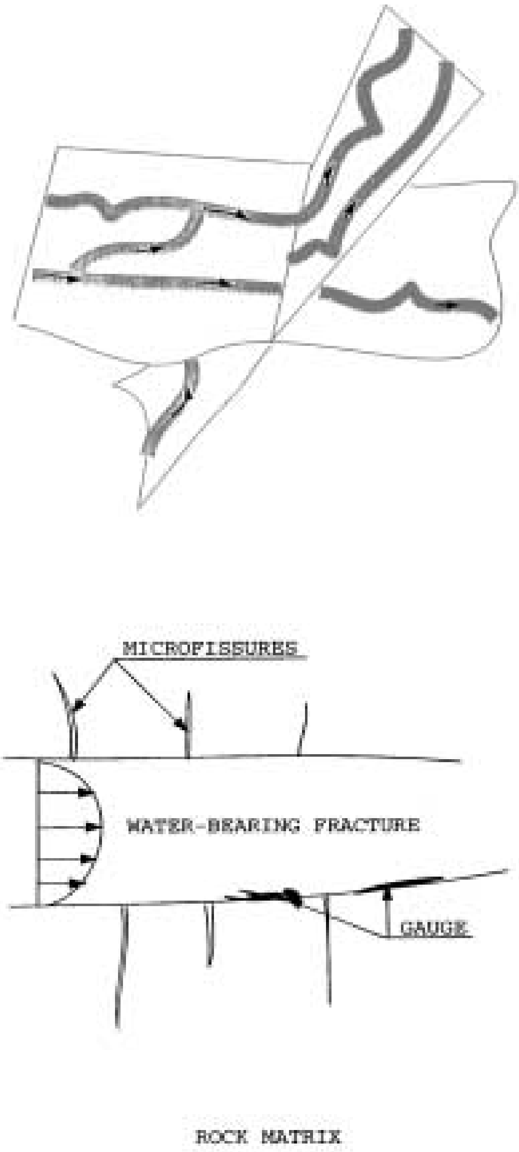


Figure 3-1. *Illustration of processes leading to dispersion of a tracer pulse. Two intersecting fracture planes (top) and micro-scale processes.*

The basic idea of PARTRACK can be described as follows, see also Figure 3-2:

- A particle entering a scalar cell will, if no dispersion effects are activated, travel through the cell in a time which is equal to the free volume of the cell divided by the flow rate through the cell (a so called plug-flow). If dispersion effects are active the travel time will, however, be different and will also be different for different particles.
- When the particle is ready to leave the cell, it will leave through one of the cell walls that has an outgoing flow direction. The choice between cell walls with an outgoing flow is made with a likelihood that is proportional to the outflows. If several particles are traced the cloud will thus split up in proportion to the flow rates. Complete mixing in a cell is hence assumed.

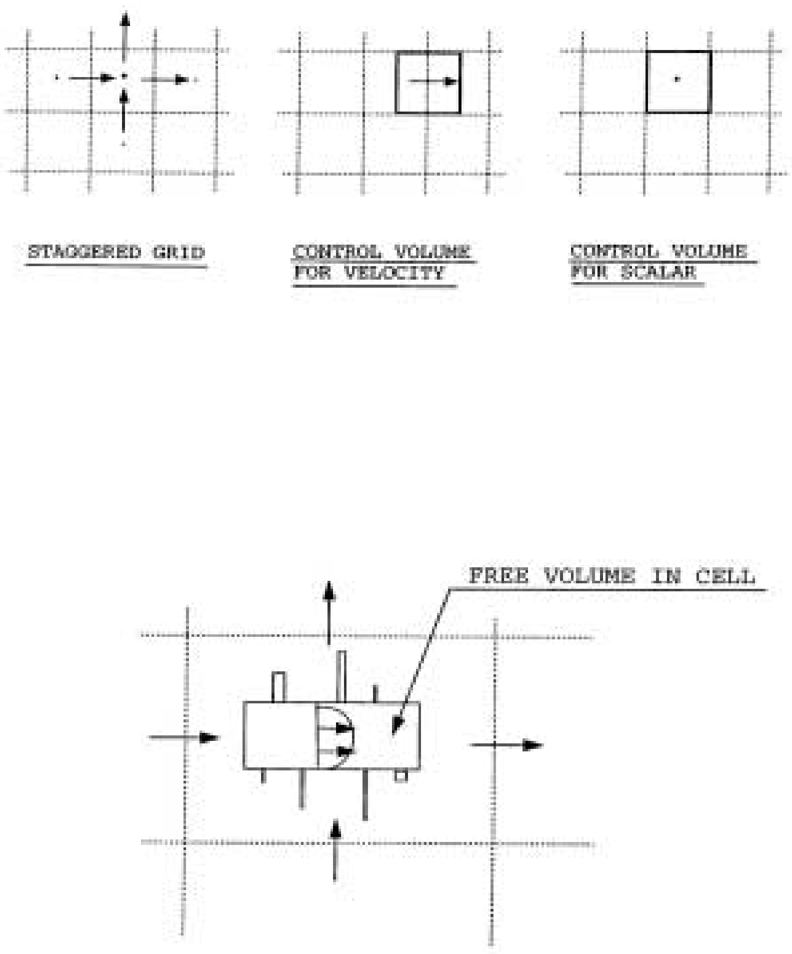


Figure 3-2. *Illustration of concepts in the flow model (top) and subgrid processes affecting a particle's travel time.*

Some basic concepts about PARTRACK with multiple particle states are briefly described below.

Consider the laminar velocity profile shown in Figure 3-3. The velocity profile is not simulated in the flow model but an average pore velocity is obtained as a result of the flow calculation. The dispersion effect of the velocity profile can now be simulated by imaging a number of states a particle can be in and ascribe different velocities to each state; the states may be considered as different layers in the velocity profile, see Figure 3-3. One may also like to simulate that a particle can get sorbed on the fracture wall, which then introduces one more state a particle can be in. Assume that five states are defined for the simulation of Taylor dispersion and one state for sorption on the fracture wall. The definition of how a particle may move between the different states is then done by the intensity matrix, shown in Figure 3-3. The first column gives the conditions for state one (the sorbed state). As can be seen, it only has a certain probability to move to state two, which is the first layer in the fracture. The second column gives the conditions for layer one (state two) and so on. It can be shown that the frequency value for change between two layers in the fracture is D_{mol} / Δ^2, where D_{mol} is the molecular diffusivity of the substance and Δ the layer thickness.

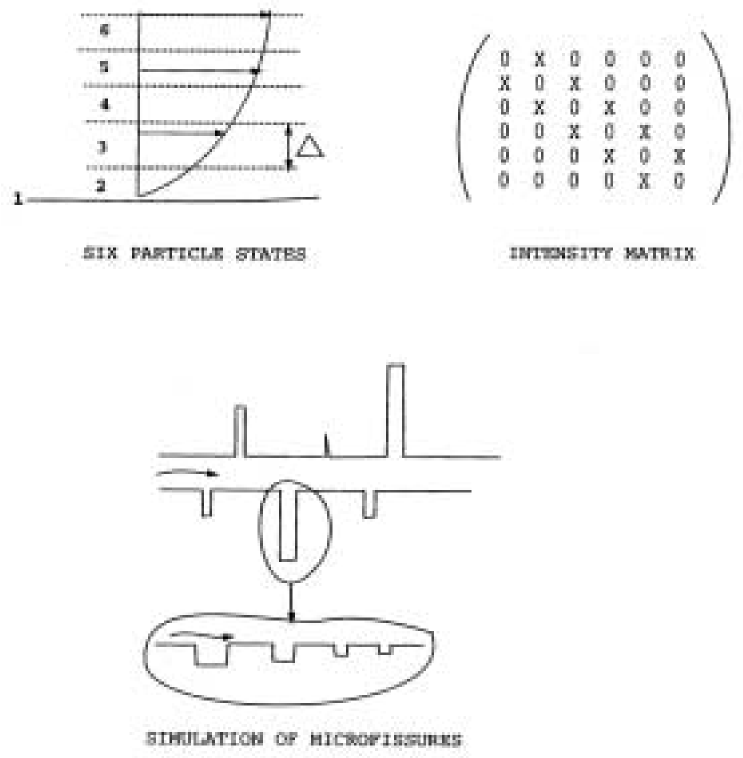


Figure 3-3. *Illustration of particle states in PARTRACK.*

To verify that PARTRACK predicts the same breakthrough curves as the multi-rate model by McKenna /1999/, for a range of tracers with strongly varying sorptivity, the dat set as in McKenna /1999/ was used. Good agreement is found, see Figure 3-4, except for early arrival times, which may be due to different concepts used for mechanical dispersion.

The simple fracture network in 3D was used to demonstrate simultaneously acting processes. The resulting breakthrough curves can be studied in Figure 3-5. When no dispersion processes are activated (solid curve) it is possible to identify the peaks that are due to the different pathways. When Taylor dispersion is added these peaks are masked. A variable aperture field gives some additional dispersion due to the channelling effect. The multi-rate diffusion process adds a long tail to the breakthrough curve.

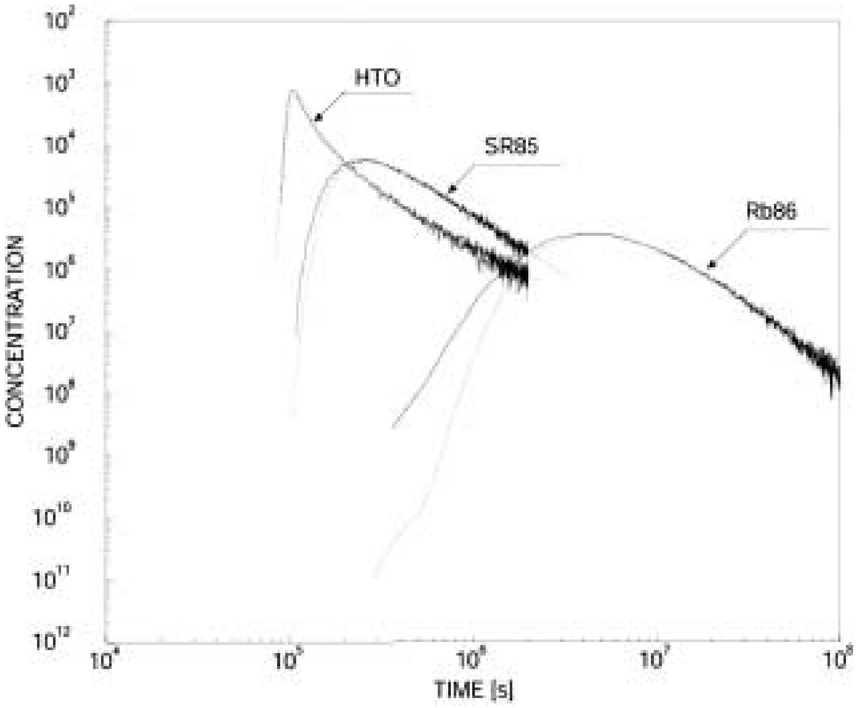


Figure 3-4. The multi-rate model. Comparison of breakthrough curves for tritiated water (HTO), Sr85 and Rb86. Dotted lines give the results from the model by McKenna /1999/.

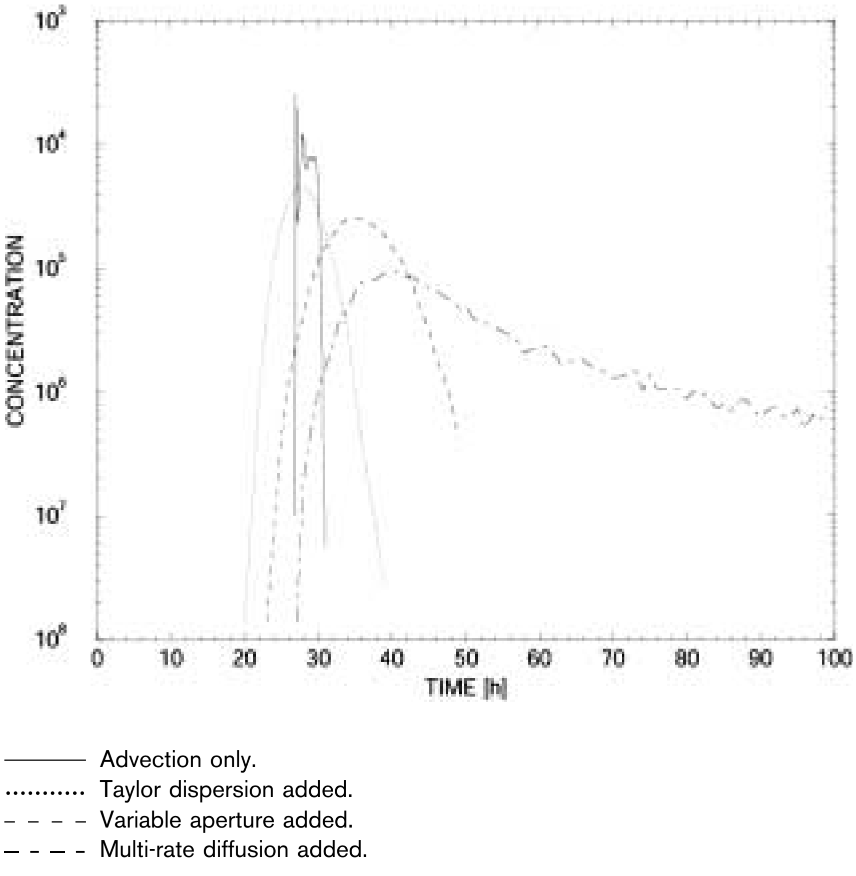


Figure 3-5. Simultaneously acting processes. Breakthrough curves.

Representation of porosity and connectivity in a continuum model

Representation of porosity and connectivity in a continuum model has been studied. If only a steady state solution is sought, the porosity and connectivity structure will mainly influence the dispersion of salt. For a transient simulation all aspects of the porosity and connectivity structures will, however, be of crucial importance. The main reasons for this are:

- The advective transport velocity of salt is determined from the Darcy flux and the kinematic porosity (to be discussed and defined below).
- Dispersion of salt is in principle a manifestation of different flow paths (on several scales) and hence related to the porosity and connectivity structures of the rock.
- Stagnant volumes in the rock may store large water volumes for very long time periods. If the long time evolution of the water chemistry is to be studied, it is essential to characterise the stagnant volumes and their connections to the "moving" water.

The analysis is focused on a sparsely fractured rock, as typically found at the Äspö HRL. It will be assumed that flow only takes place in the fracture network, i.e. flow in the matrix is neglected. In Figure 3-6 different parts of the network have been marked with letters; these will now be described:

A: Represents a fracture zone. The fracture zone is assumed to be composed of a number of smaller fractures through which the flow takes place. Most of the small fractures do, however, not contribute to the flow but are still important for transport and dispersion of a tracer. Fracture zones are often the main flow conductors due to their high transmissivity and size (length scale > 100 metres). The thickness is typically > 1 metre.

B: Some fractures are best characterised as "a single opening". Typically the thickness, or the aperture, is on the order of 10^{-3} metres. The fractures marked with **B** in Figure 3-1 have a through-flow and may hence contribute to the total flow rate. If the transport time through the **B** fractures is different from the transport time in the fracture zone a dispersion effect will also result from the parallel flow path.

C: Isolated fractures or groups of fractures cannot contribute to the flow, transport or dispersion, as flow in the matrix is neglected. In the numerical model these are removed before the generation of grid data is performed.

D: Some fractures, or fracture zones, may form "dead end systems". The exchange with fractures with a significant flow is then by molecular diffusion. When storage of water over long time periods, say longer than 100 years, is studied it is essential to represent the dead end systems correctly.

E, F: There is always a lower limit on the fracture size that can be represented correctly in a numerical simulation. In the present study it will be assumed that fractures below a certain size, to be discussed, do not contribute significantly to the total flow. However, for transport and dispersion it is probably necessary to consider all scales as a large fraction of the pore volume, is expected to be due to the small-scale features of the porosity field.

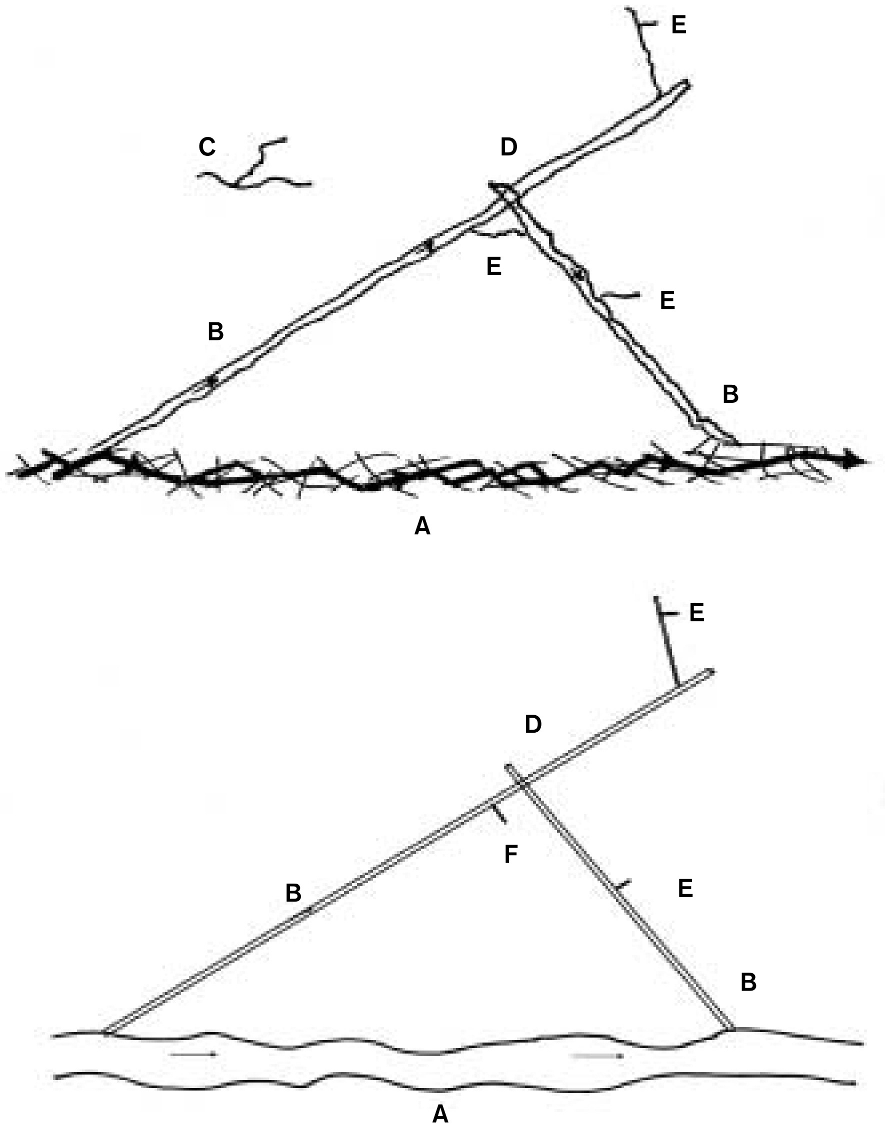


Figure 3-6. *Representation of the real world fracture network as conductive elements and storage volumes.*

When a conductive element intersects a grid cell, grid cell values are generated. It should be noted, though, that the conductive element generates all kinematic properties of the cell, while other volumes in a fracture or zone will be represented as storage volumes, see Figure 3-7.

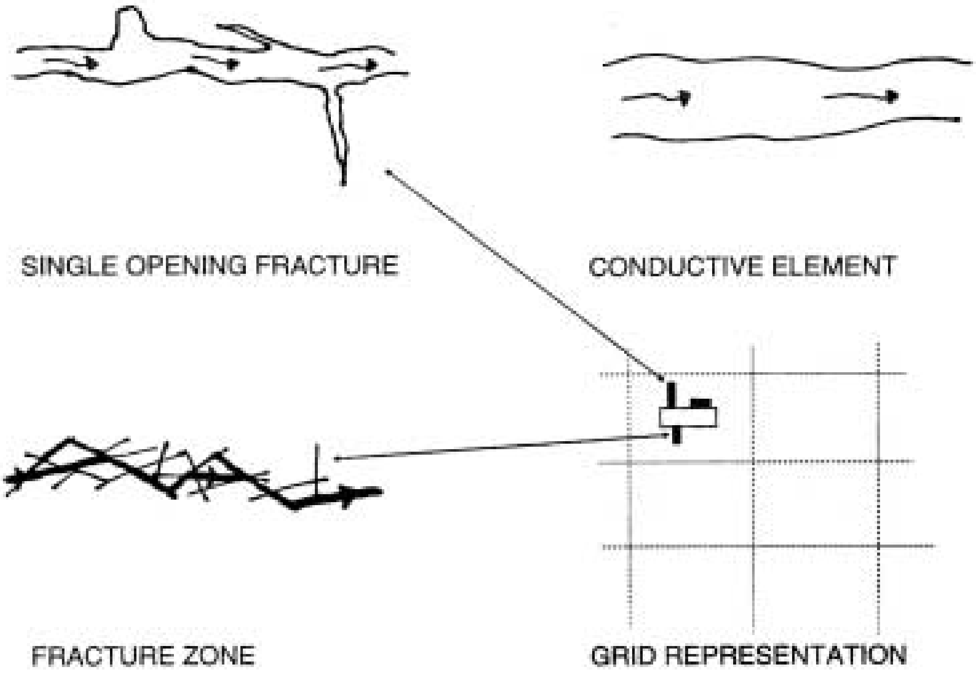


Figure 3-7. *Representation of kinematic and storage volumes in the grid. The open rectangle in the grid represents a kinematic volume (generated by the conductive element), while filled rectangles represent storage volumes.*

To simulate the mass transfer within a storage volume one needs to solve a 1D diffusion equation. However, as has been shown by Haggerty and Gorelick /1995/, it is possible to simulate the transport within the storage volume by a series of boxes that exchange matter with the kinematic volume; see Figure 3-3.

In one of the test cases data from the Äspö site was used. For a head gradient of 10^{-3}, it is found that disregarding all cells with a maximum absolute cell wall flux of 3×10^{-11} m/s will result in a decrease of the average flux through the domain that is smaller than 1%. Here "stagnant cells" is cells with a cell wall flux of 3×10^{-11} m/s or less. In Figure 3-8 three porosity fields are shown; in the top one all generated fractures contribute to the porosity field, in the middle one all isolated volumes are disregarded and in the lower one also the stagnant volumes have been removed. It is clear that most of the flow is due to a limited number of fractures.

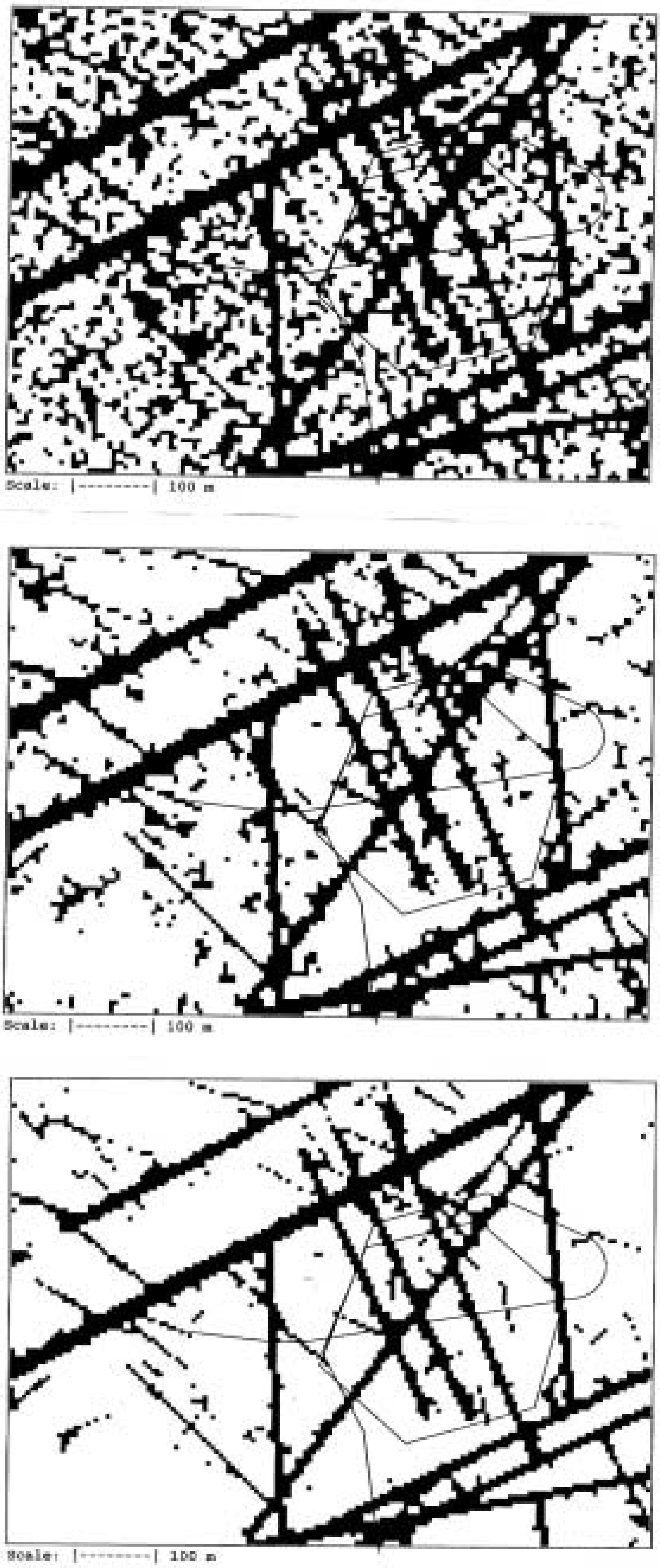


Figure 3-8. *Kinematic porosity fields at a depth of 450 metres, based on all generated fractures (top), all connected fractures (middle) and all connected fractures disregarding stagnant volumes.*

Storage volumes, see Figure 3-7, are connected to the kinematic porosity. It is expected that these volumes are 10–100 times larger than the kinematic volumes. They are not important (except through the storativity term) in flow simulations but need to be considered in transport calculations. A visualisation of the kinematic porosity (n_c) and flow field is shown in Figure 3-9.

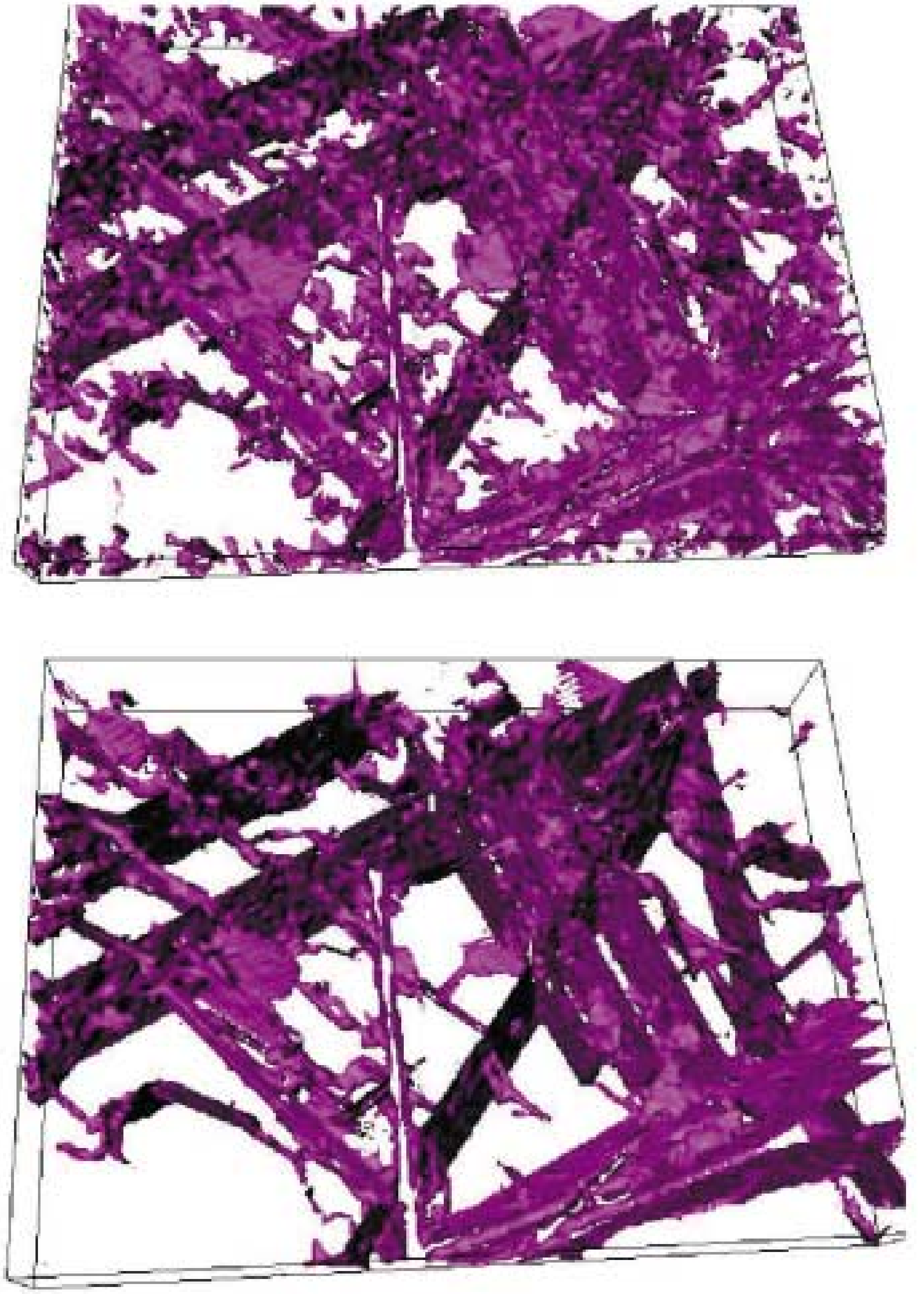


Figure 3-9. *Illustration of porosity (top) and flow fields. Depth interval shown is 400 to 500 metres below ground level. The flow is from west to east. View from south.*

The next case deals with long time storage of water. Also in this case a steady flow from west to east is used. The initial condition is a tracer concentration of 1.0. The concentration of the inflowing water is 0.0 and the mean concentration in the domain will hence decrease. If no storage volumes are active the concentration in the domain will be rapidly decreasing; it is close to zero everywhere after about 100 years. With storage volumes included, a significant amount of the tracer is still in the domain after 1000 years, see Figure 3-10.

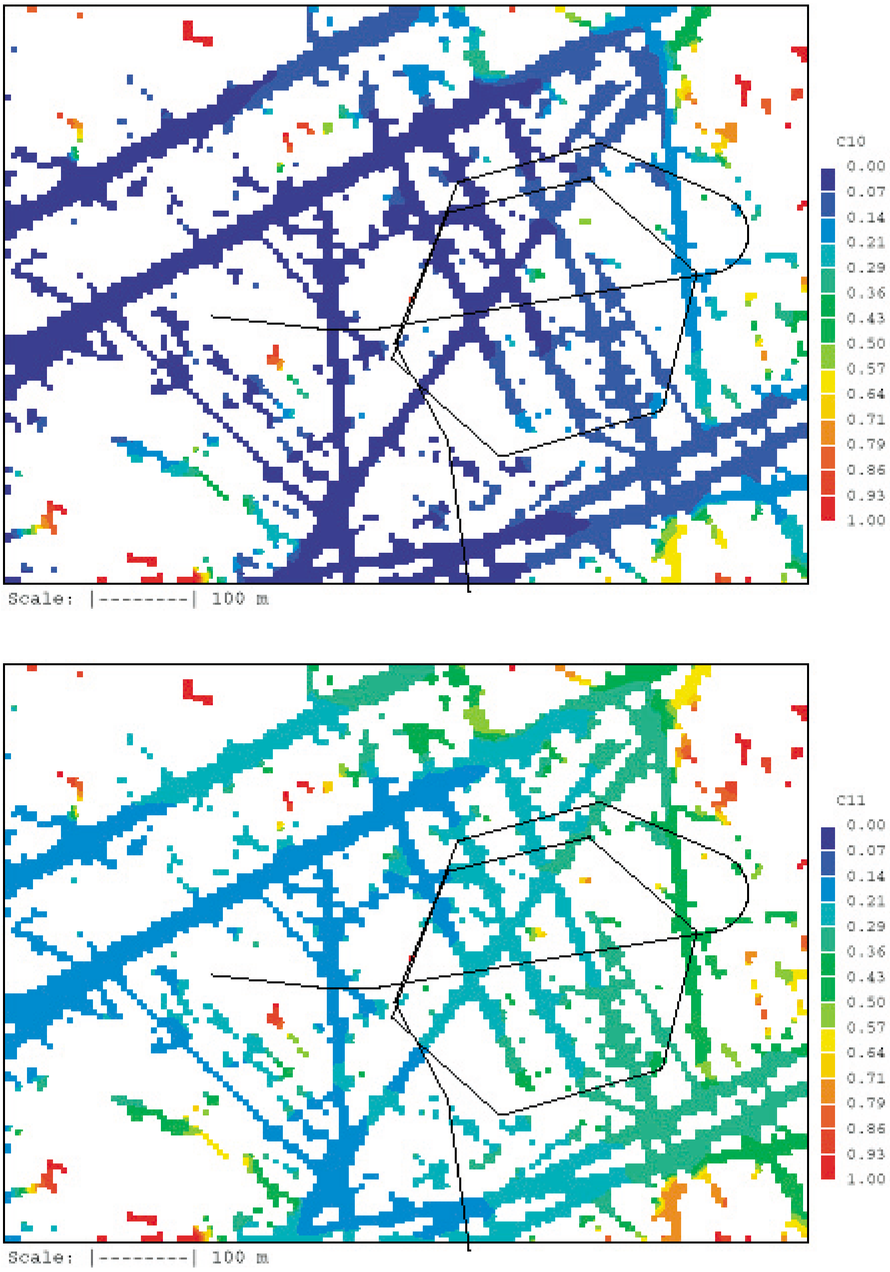


Figure 3-10. *Illustration of long time storage of water. Tracer concentration in "kinematic volumes" (top) and in storage volumes, after 1000 years of integration.*

A qualitative study of the gravitational effects was carried out. As in the previous case a pressure gradient was specified in the west to east direction. The inflow and outflow sections were, however, now limited to a 10 metres high horizontal band at a depth of 380 metres. The initial salinity in the domain was zero, while the inflowing water had a salinity that varies in time, according to the different stages of the Baltic Sea. The total integration time was 10 000 years. What one can expect is that the salt water will replace the water in the lower half of the domain, while some water with zero salinity may remain (note that the inflowing water always has a salinity > 0%) in the upper half of the domain.

The result after 10 000 years of integration can be studied in Figure 3-11. The two vertical sections show the result with (top) and without gravity activated. Obviously gravity is a very important factor when storage of old water types is to be analysed.

A comment may be needed on the "horizontal band of 10 metres" giving the inflow and outflow boundaries. The salinity of the inflowing water is intended to illustrate different stages, with different salinities, of the Baltic Sea. In the present model set-up we do not simulate the contact with the Baltic Sea, as the top of the model domain is at a depth of 200 metres, and we are thus forced to specify "unrealistic" boundary conditions. It should, however, be noted that the purpose of the simulation is to illustrate the effect of density variations, in a qualitative way.

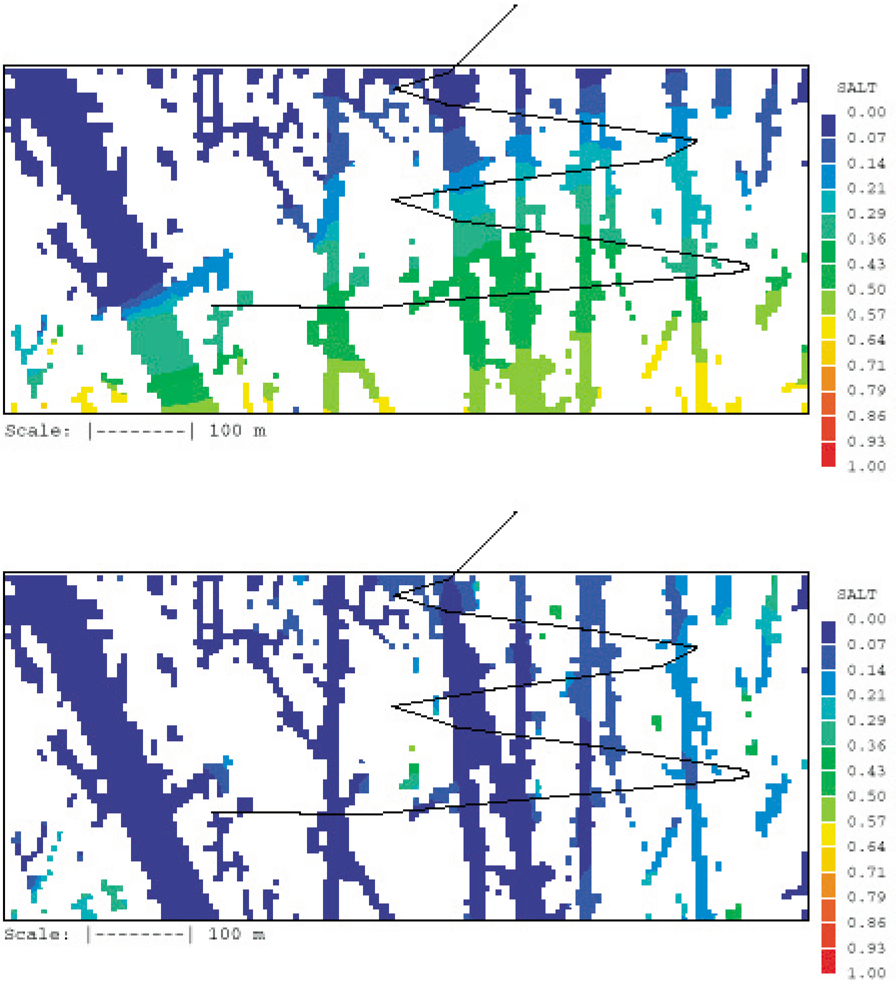


Figure 3-11. *Effect of gravity. Vertical sections, West(left)to East (right), of salinity field after 10 000 years of integration with (top) and without gravity activated.*

3.3 Tracer Retention Understanding Experiment

3.3.1 TRUE-1

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 TRUE experiments 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 for radionuclide transport 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 2 years. At the end of each test cycle, results and experience will be evaluated and the programme revised.

The basic idea is to perform a series of 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 resin will be injected. Subsequently the tested rock volume will be excavated and analysed with regards to flow path geometry, and tracer concentration.

The first tracer test cycle (TRUE-1) constitutes a training exercise for tracer testing technology on a detailed scale using non-reactive tracers in a simple test geometry, see Figure 4-1. In addition, supporting technology development is performed for sampling and analysis techniques for matrix diffusion, and for understanding of tracer transport through detailed aperture distributions obtained from resin injection. The TRUE-1 cycle is expected to contribute data and experience, which will constitute the necessary platform for subsequent more elaborate experiments within TRUE.

The stated objectives of the first tracer test cycle (TRUE-1) are:

- To conceptualise and parametrize an experimental site on a detailed scale (L=5 m) using non-reactive tracers in a simple test geometry.
- To improve tracer test methodologies for non-reactive tracer tests on detailed scale.
- To develop and test a technology for injection of epoxy resin on a detailed scale and to develop and test techniques for excavation (drilling) of injected volumes.
- To test sampling and analysis technologies to be employed in the analysis of matrix diffusion.

During 1995 work within the TRUE experiment has mainly been devoted to site characterisation of the site where the tracer experiments during the First TRUE Stage will be conducted, and development of resin injection technology.

Late 1995 SKB identified the need for early data on reactive tracer transport and took the strategic decision also to include reactive transport experiments during the First Tracer test cycle. Early 1997 preparatory work at the site commenced at the test site with furnishing of two containers to host the injection and pumping equipment. A series of design tests (PDT-1 through PDT-3) were performed during the Spring. The first of the tests with radioactive sorbing tracers (STT-1) was started up mid July 1997 and comprised injection of Na. Ca, Sr, Rb, Ba and Cs in the flow path KXTT4-> KXTT3. The results showed a strong retardation of Cs-137. Late 1997 it was decided to prolong the study of Cs breakthrough. It was also decided to conduct an additional injection in the same flow field, but in a different flow path (KXTT1 -> KXTT3). The latter injection included the same tracers as in STT-1 with the exception that Cs-137 and Br-133 were not included, and with the addition of the two radioactive conservative tracers, I-131 and Br-82, the sorbing tracer Co-58 and the redox-sensitive tracer Tc-99m. The latter test is denoted STT-1b.

During 1998 the flow path between KXTT4 and KXTT3 was revisited with a new test with sorbing tracers using a flow rate of 0.2 l/min, i.e. 50% of the flow rate employed during STT-1. Apart from radioactive sorbing tracers employed during STT-1 and STT-1b, also the K-42 and the redox-sensistive tracer Tc-99m were used, the latter which did not show breakthrough. The breakthrough curves, unlike the ones observed for STT-1, show dual peaks, most distinctively in the breakthrough of the conservative tracers, indicating transport in two flow paths. Indeed, two intercepts have been interpreted in section KXTT4:R3. The fact that a dual peak is observed in STT-2, and not in STT-1 is attributed to the 50% reduction in pumping rate, sufficient to activate the subordinate flow path not mapped by STT-1.

Evaluation of the tests has been performed using what we refer to as the Lagrangian Stochastic Advection Reaction model (LaSAR) /Cvetkovic et al, 1999/. In this approach the flow path is viewed as part of an open fracture. The key processes are spatially variable advection and mass transfer, the latter assumed linear, and the coupled effect is obtained by convolution. To account for dispersive effects, the convoluted result for a single flow path is integrated over different flow paths, described by a distribution of τ and β. The parameter β [T/L] is flow-dependent, integrating the inverse of the velocity-weighted aperture along the a flow path, and τ is the water residence time. The product $q\beta$ [L^2] provides an estimate of the area over which the tracer is in contact with the rock matrix ("flow-wetted surface"), where q [L^3/T] is the volumetric flow rate carrying the tracer. The parameters β and τ have been shown to be significantly correlated for generic conditions /Cvetkovic et al, 1999/ and also for Feature A specific conditions, such that an approximate linear (deterministic) relationship $\beta = k \cdot \tau$ is applicable. Using Monte Carlo simulations of flow and particle transport in Feature A, we estimated $k_0 \approx 3400$ m^{-1} as an ensemble average. For the strict assumption of linear relation between β and τ, k is equivalent to the "flow wetted surface per volume of water" (a_w) as defined and used in the recently concluded safety analysis SR 97 /SKB, 1999/. The sorption parameters for the fracture are the distribution coefficients for surface sorption K_a and sorption in gouge K_d^g. The key parameter group controlling sorption/diffusion into the rock matrix is $\beta\kappa$ $[T]^{½}$ where $\kappa = \theta[D(1+K_d^m)]^{1/2} = \theta(DR_m)^{1/2} = (\theta F D_w R_m)^{1/2}$, where θ is the porosity of the rock matrix (note that no distinction is made between the "total porosity" and the "diffusion porosity"), F is the formation factor and D and D_w are the pore diffusivity in the rock matrix (θD is the effective diffusion coefficient in the rock matrix) and the diffusivity in water, respectively. K_d^m is the sorption coefficient in the rock matrix. The evaluation includes determination of the water residence time distribution $g(\tau)$ by deconvoluting breakthrough curves for tritiated water (HTO). The reactive breakthroughs are evaluated using $g(\tau)$. One of the stated hypotheses is that the laboratory-derived value of κ may not be representative of the corresponding value in the field.

During the year the final report of the First TRUE Stage was published /Winberg et al, 2000/.

The basic results and conclusions drawn by the SKB project group are:

- Feature A follows a reactivated mylonite, exposed to brittle deformation which has formed the main fault plane = main conductive element. One undulating structure, or alternatively several interconnected fractures. Bounded by a rim zone of altered Äspö diorite. Different mineralogical composition, grain size and porosity relative to the mylonite. Indications of clay minerals suggest presence of gouge material.
- Available tracer test methodology successfully adapted and applied in the detailed scale under prevailing conditions.
- Cationic sorbing tracers featured by sorption through cation exchange successfully applied in laboratory experiments and in in situ experiments. The sorbtivity of the tracers show the relative order; $^{22}Na^{+} < {}^{47}Ca^{2+} \approx {}^{85}Sr^{2+} < < {}^{86}Rb^{+} \approx {}^{133}Ba^{2+} < {}^{137}Cs^{+}$.
- Unlimited diffusion/sorption in the rock matrix is the dominant retention mechanism for the tested time scales. Surface sorption, limited sorption in gouge material and diffusion into stagnant zones are second order for the strongly sorbing tracers.
- The use of laboratory data on diffusion/sorption parameters constitutes a basis for predictions of reactive tracer breakthrough, this provided that the water residence time distribution (conservative breakthrough) is known (can be assessed) and that variability in the β parameter is accounted for.
- The important processes identified at the time scales of the TRUE-1 in situ experiments are assumed valid also over PA time scales. Laboratory transport data on unaltered rock, not associated with fracture rim zone, are assumed applicable over PA time scales.
- The performed characterisation provides a powerful set of tools for assessment of conductive geometry and connectivity in future preliminary site characterisation, and in particular during future detailed site characterisation.

The results obtained and conclusions drawn were presented and discussed at an international seminar. At the seminar, not only the results and conclusions of the experimental team were presented, but also those of other analysts whom have worked on the TRUE-1 data. Furthermore, results of studies with similar goals performed elsewhere were reported and discussed. Using the outcome of the ensuing discussion a number of overall conclusions were drawn.

Outcome from 4th International Äspö seminar

- There is a general consensus that the observed retardation observed in the TRUE-1 experiments requires diffusion into geological material to be an active process. This supported by the –3/2 slope noted in log-log breakthrough curves. Whether this is due to diffusion (and subsequent sorption) in the altered matrix rock, or in possible fault gouge cannot be differentiated with available data.
- Some researchers claim that the observed enhanced retardation may be explained by diffusion into stagnant water pools, pure surface sorption, or may be due to an underestimation in the flow-wetted surface area. The latter effect may be attributed to a more complex flow path (multi-layered structure) or three-dimensional effects.

- A clear differentiation between the principal active process can only assessed by resin injection and subsequent excavation and analysis.
- It was identified that experiments of TRUE type are important for improving the understanding of retention processes. However, this type of experiment may not necessarily be part of a site characterisation programme.
- It was recommended to broaden the data base from the TRUE-1 site before characterising pore space with resin techniques. This includes tracer dilution tests using sinks in other features than Feature A.

3.3.2 TRUE Block Scale

Background

Work on the TRUE Block Scale Project started in mid 1996. This subproject of TRUE broadens the perspective from an address of a singular feature in TRUE-1, to flow and transport processes in a network of fractures and a spatial scale between 10 and 50 m. The specific objectives of the TRUE Block Scale Project are to /Winberg, 1997/:

1. increase understanding and the ability to predict tracer transport in a fracture network,
2. assess the importance of tracer retention mechanisms (diffusion and sorption) in a fracture network,
3. assess the link between flow and transport data as a means for predicting transport phenomena.

A set of desired experimental conditions have been defined and a flexible iterative characterisation strategy has been adopted /Winberg, 1997/. The project is divided into a five basic stages:

- Scoping Stage.
- Preliminary Characterisation Stage.
- Detailed Characterisation Stage.
- Tracer Test Stage.
- Evaluation (and reporting) Stage.

The total duration of the project is planned to be approximately 5 years with a scheduled finish at the end of the year 2001.

The project was originally organised as a multi-partite project involving ANDRA, NIREX, POSIVA, and SKB. During 1997, also ENRESA and JNC has joined the project.

As of 1997 in total three boreholes, KA2563A, KI0025F and KI0023B, had been drilled into the selected rock volume. In addition an already existing borehole, KA2511A, had been used for characterisation and pressure registration.

During 1998, one additional borehole, KI0025F02, was drilled and used for site characterisation. A comprehensive 3D seismic measurement campaign was carried out with seismic sources distributed in the near proximity tunnel system and with the seismic receiver system distributed along the length of borehole KI0025F02. The obtained data has subsequently been co-interpreted with existing old seismic data from the investigated rock block. During the year a comprehensive cross-hole interference, tracer dilution and tracer test programme was carried out. During the 1998 the POSIVA flow meter was employed in a detailed mode for the first time in borehole KI0025F02.

Tentative modelling work started up during 1997 using a discrete feature network model (DFN). During 1998, the modelling work has diversified with the inclusion of stochastic continuum and channel network modelling. In addition a site scale DFN model has been constructed to allow analysis of density effects and also to generate boundary conditions for the models constructed on a smaller scale.

Also the groundwater chemical data collected from the packed off sections were used in the integrated interpretation of groundwater flow in the studied block. During the year one structural model update was produced (Sep'98 model) /Winberg, 1999/ which was presented in conjunction with the 2nd Review meeting in November 1998.

During 1999 focus was shifted towards planning and preparations for the upcoming Tracer Test Stage. Work in the field was concentrated on verifying interpreted structures and a structural model was developed based on the new field data including data from the most recent borehole KI0025F02 to form the March'99 structural model. Another important component was the performance of a Pre-test tracer test campaign which clearly demonstrated the feasibility of block scale tracer tests in the selected block. Scoping model calculations were also performed to analyse effects of fracture inter sections. In a document which provided an outline of the planned Tracer Test Stage it was recommended to drill one additional borehole to facilitate verification of the structural model and shorter transport distances. Furthermore, a list of three basic questions to be addressed by the tracer tests were formulated and a corresponding set of hypotheses were defined. The plans for the Tracer Test Stage were discussed at the 3rd TRUE Block Scale Review Meeting in October 1999.

The plan to drill a new borehole (KI0025F03) was accepted and was drilled and characterised during the Fall of 1999.

Results

Hydro-structural model and conceptualisation

The most recent model update, the March'00 model, cf Figure 3-12, is based on the characterisation data from the new borehole KI0025F03. In building the model the new and existing hydrauliuc data has been used to reconcile the model /Hermanson and Doe, 2000/. The basic components included in the March'99 model are found to be valid. One structure, #23, only tentatively indicated in the latter model, was confirmed by the characterisation performed in the new borehole. The new model also features an new structure, #24, north of Structure #6, although with limited relevance to the tests planned for the Tracer Test Stage.

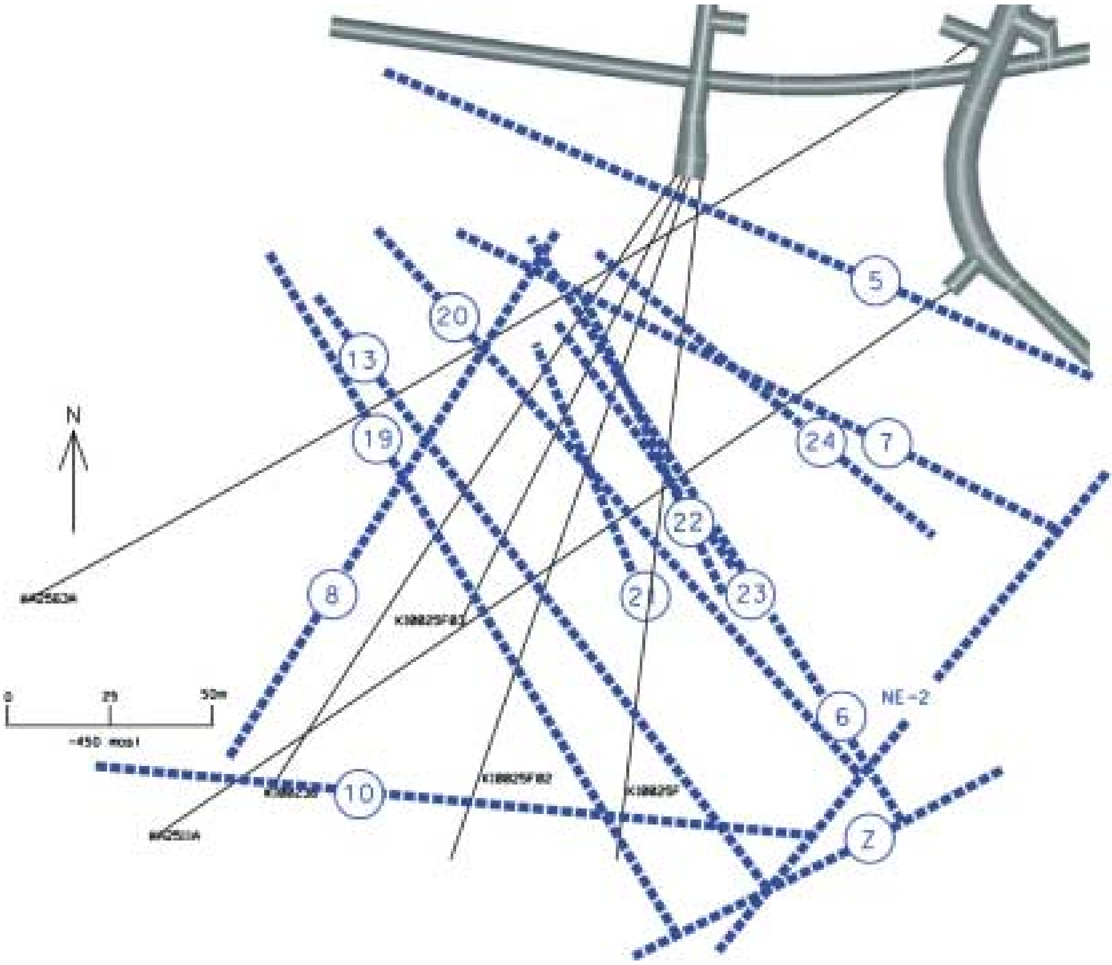
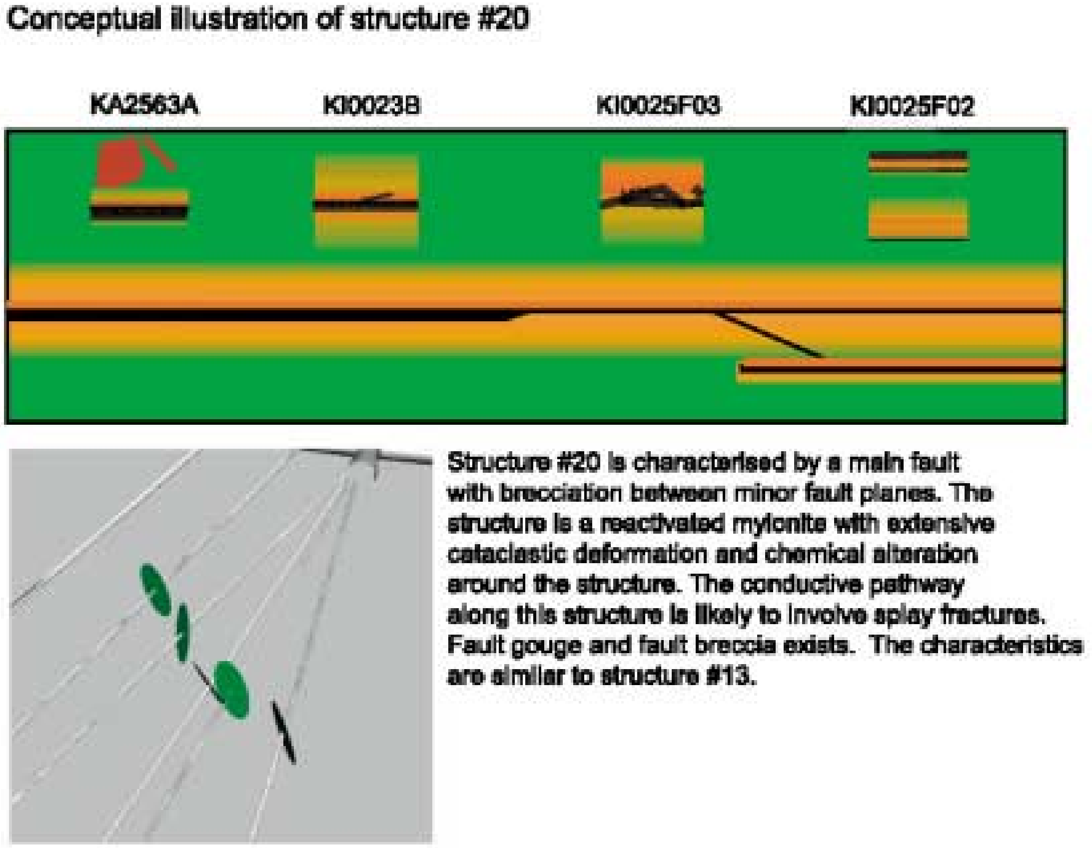


Figure 3-12. *March 2000 hydro-structural model.*

As part of the preparations for the numerical model predictions of the planned tracer tests, simplistic conceptualisations of individual intercepts of interpreted deterministic structures, as well as composite structural models of interpreted structures along their extent have been constructed. An example of the latter is given cf Figure 3-13 for Structure #20.

Retention properties

No site specific through diffusion or batch sorption experiments have been performed on materials from TRUE Block Scale. However, a comprehensive mineralogical and geochemical analyses programme has been performed. This has involved analyses made on altered wall rock, fault breccia pieces (> 2 mm) and the smallest fraction (< 2 mm), the smallest fraction < 0.125 mm. Of the latter some 15–45 weight % comprise the fraction < 0.002 mm featured by a variable degree of enrichment in clay minerals, calcite, pyrite and FeOOH. Using the measured water chemistry and mineral-specific cation exchange capacities reported in the literature, integrated caion exchange capacities were calculated for the fine-grained fault gouge material (< 0.125 mm). Subsequently,



Structure #20 is characterised by a main fault with brecciation between minor fault planes. The structure is a reactivated mylonite with extensive cataclastic deformation and chemical alteration around the structure. The conductive pathway along this structure is likely to involve splay fractures. Fault gouge and fault breccia exists. The characteristics are similar to structure #13.

Figure 3-13. *Schematic conceptual model of Structure #20 based on detailed conceptualisations from individual borehole intercepts.*

by applying the cation exchange sorption model, the sorption distribution coefficient Kd for the mono- and divalent cations to be used as tracers in the planned Phase C were calculated.

Collected geological samples from structures of interest in the TRUE Block Scale Rock Block have also been subject to porosity determinations. Two techniques have been employed; the water saturation technique and the ^{14}C PMMA method /e.g. Hellmuth et al, 1999/. Porosity determinations with the two methods have been done on three types of materials; altered wall rock, centimetre sized pieces of fault breccia, and millimetre sized fragments of fault breccia. For the first time the PMMA technique was applied to such small fractions of crystalline rock. The global picture, which emanates from the water saturation measurements is one with a porosity of the intact Äspö dirite bedrock of 0.45%, and where the higher extreme is found for the fault breccia fragments with a porosity range of 1.5 to 3%. A sample visualisation of the distribution of porosity in a fault breccia piece from the interpreted Structure #20 is shown in Figure 3-14.

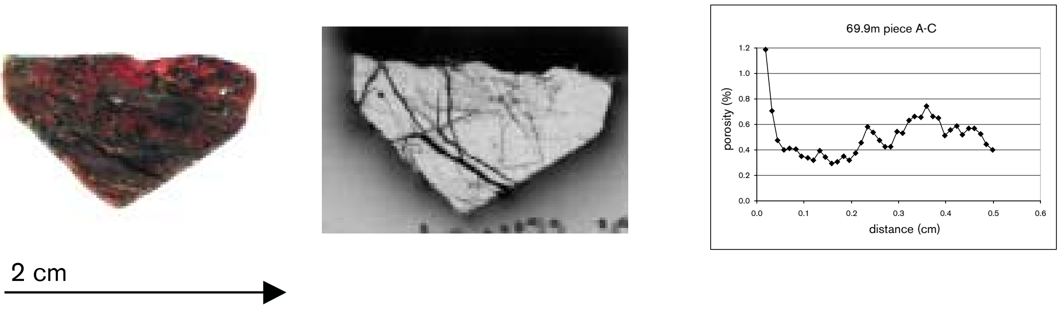


Figure 3-14. *Autoradiograph of a fault breccia piece from Structure #20 KI0023B, L=69.9 m, 9 days. An adjoining image also shows the porosity distribution in the sample.*

Tracer tests

The basic plans for the Tracer Test Stage included a sequence of three phases, denoted A through C. Phase A /Andersson et al, 2000a/ was focused on identification of suitable injection sections using tracer dilution tests (Tests A1 through A3) and on identification of the best suitable sink sections (tests A4 and A5). The latter tests were deliberately not continued to full breakthrough because of time constraints. The principle objective of Phase B /Andersson et al, 2000b/ was to demonstrate sufficiently high mass recovery (> 80%) of selected flow paths and also to demonstrate matrix diffusion through the use of dissolved He-3 gas. The final Phase C comprised performance of a series of four injections with radioactive tracers in three different flow paths involving one or more of the interpreted structures.

Phase A tests

The performed tracer dilution tests (Tests A1–A3) were found to generally confirm the March'99 hydro-structural model and performed short-time interference tests in KI0025F03 /Andersson et al, 2000a/. Flow responses from tracer dilution tests generally correlate to sections with high drawdown. The tracer dilution tests in 53 different sections showed that the "natural" flow vary considerably within the Block Scale rock volume. An extremely high flow rate (11 l/h) was measured in KI0023B:P7 where a short-circuit between structures #6 and #20 exists. The flow rates in the other measured sections typically were in the range 0–300 ml/h. There are also variations in the "natural" flow between the different tests for some sections.

Based on the results from tests A-1 to A-3, the best alternative sink to the already tested KI0023B:P6 (#21) was selected for test A-5. As test A-2 showed somewhat less good connectivity the final choice was between the A-1 and A-3 sinks, KI0025F03:P5 and KI0025F02:P5, both packing off Structure #20. The final choice fell on the A-1 sink, KI0025F03:P5, based on i) the possibility to address the effects of fracture intersections, ii) that some of the sections with very good flow responses are located in KI0025F02 and therefore would be easier to use as potential injection points (better defined flow path).

The tracer test in A-4 performed by pumping in structure #21 (KI0023B:P6) resulted in tracer breakthrough from two of three injection points, KI0025F03:P5 (Structure #20) and KI0025F03:P6 (#22), cf Figure 3-15. No breakthrough was observed from injection in section KI0025F03:P7 (#23). The tests cover Euclidean distances ranging between 14 to 17 m, which probably are longer in reality. The tracer mass recoveries are not very

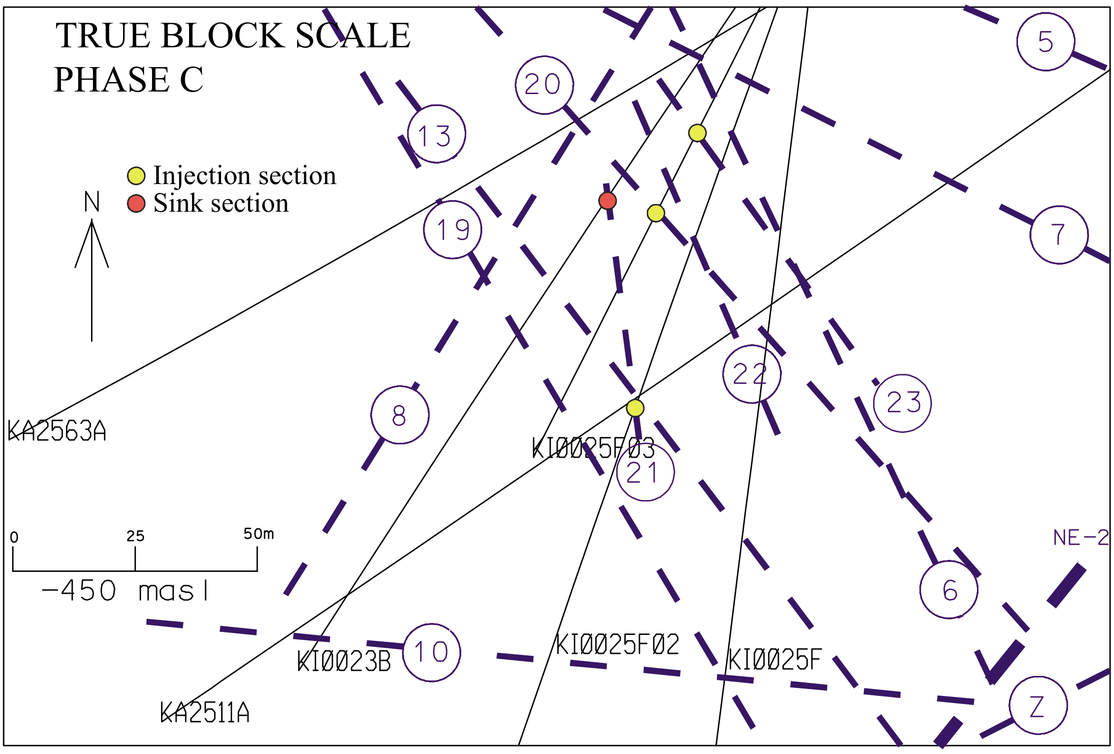


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Figure 3-15. *Detail of March'99 Structural model showing the layout of pumping section and injection sections used in the Phase B tests. The figure also provides means to identify the sink and source sections used in the Phase A and B tests.*

high (30–40%) but a large portion of the tail of the breakthrough curves still remained to be recovered when sampling was finished, and therefore it is likely that the mass recoveries would have increased by another 20–30%.

The tracer test in A-5, cf Figure 3-15, performed by pumping in Structure #20 (KI0025F03:P5) resulted in tracer breakthrough from four of five injection points, KI0025F02:P5 (Structure #20), KI0025F02:P6 (#22), KI0025F03:P6 (#22) and KA2563A:S4 (#20). No breakthrough was observed from injection in section KI0025F02:P3 (#13, 21). The tests cover Euclidean distances ranging between 11 to 29 m, which probably are longer in reality.

Based on the results from the analysis of the tracer tests performed during tests A-4 and A-5 together with previous tracer tests performed (PT-4) a final choice of sink for the planned tracer tests during Phase B and C of the Tracer Test Stage was done. The planned tests include injections of radioactive sorbing tracers that require high mass recovery and good control of the experiments. Test A-5 only provided one or maybe two flow paths with high enough mass recovery whereas test A-4, using KI0023B:P6 as sink gave at least four possible injection points. Thus, the latter sink was proposed to use for the planned tracer tests in Phase B and C.

Phase B tests

The Phase B tests /Andersson et al, 2000b/ involved a total of ten different test set-ups, the three first (B-1a through c) with tracer injection in three different flow paths at a reduced withdrawal rate (Q=1.2 l/min) at the sink and the remaining seven tests (B-2a through g) with maximum withdrawal rate (Q=2.1 l/min) at the sink. All tests used the same sink section KI0023B:P6. Two of the flow paths were also tested using Helium and a reference tracer to study diffusion effects.

The tracer injections were mostly performed by injecting with a constant flow throughout the entire duration of the test creating an uneven dipole flow field with injection flow rates in the order of 0.5–2% of the withdrawal rate. The main reason for using this technique was to increase the mass flux in the injection points and thereby also increase the possibility of detecting the tracer at the sink. Earlier tracer injections have preferably been performed in sections having high induced groundwater flow (measured by tracer dilution tests), while in Phase B most injection sections had low induced flow. This strategy turned out quite successful as tracer breakthrough was measured from all ten injections made.

Four of the Phase B tests were performed with the objective to study diffusion effects making use of injection of dissolved Helium (He-3). The tests were performed in two different pathways, one "single fracture path" (KI0025F03:P5) and one "network path" (KI0025F03:P6). The He and the reference tracer breakthrough curves show that Helium is delayed and has a more pronounced tailing than the reference tracer. The lower and delayed He peak indicates that diffusion as a transport process is more accentuated by the diffusive He. The longer tailing of the He breakthrough curve can also be explained by the more diffusive He. However, a more thorough analysis is needed to distinguish the interpreted effects of diffusion from phenomena which can give rise to similar results (e.g. heterogeneity, multiple flow paths). Another explanation for the difference may be effects of fracture intersection zones (FIZ) and this will be further analysed as a part of the Evaluation and Reporting Stage.

The analysis and interpretation of the breakthrough curves reveal differences between the flow paths that indicate whether the transport occurs within a single fracture or within a network of fractures. The interpretation is generally consistent with the March'00 structural model /Hermanson and Doe, 2000/ but in two cases attributed single fracture flow paths show breakthrough characteristics that indicate transport through a network of fractures. One of these paths is also interpreted to be close to a fracture intersection zone, and one possible alternative explanation could be that transport occurs along this intersection having an enhanced pore volume and thus, decreasing the transport velocity. Another explanation may be that the involved structure (#21) is discontinuous or consists of several sub-parallel structures making up a much longer travel distance than the geometrical one.

The tests have provided input for selection of flow paths suitable for subsequent tests with sorbing tracers (Phase C). A requirement is to use flow paths with high tracer mass recovery. Based on the results such flow paths are those which connect sections KI0025F03:P5 (#20), KI0025F03:P7 (#23) and KI0025F02:P3 (#21) with the selected pumping section KI0023B:P6 (#21), cf Figure 3-15.

Phase C tests

The Phase C tests were made using the results of the Phase B tests as a base, and injection of the radioactive tracers were made without interrupting the continuous pumping in KI0023B:P6 at Q=2.1 l/min.

The injections were made in a radially converging flow geometry using basically the same equipment and methodology for injection/sampling and analyses used for TRUE-1. In sections with low flow rates, the tracer will be forced into the flow path by applying a slight excess pressure using an external injection pump. The projected excess pressure created by the injection flow rates were assumed to produce strongly unequal strength dipole flow fields. The location of the injection sections in relation to the pump section is shown in plan view in Figure 3-15. One flow path (C2) is in an interpreted single structure, one is made up of two structures (C1) and one is made up of > 2 structures (C3). The injection C4 (in the same path as C1), constitutes a test of radionuclides with a sorption mechanism governed by partial radiolysis and surface complexation.

Table 3-1. Listing of tracer injections made as part of Phase C tracer tests (C-1 though C-4). The structural interpretation and notation refers to the updated and reconciled March 2000 model /Hermanson and Doe, 2000/. Distances within brackets are calculated along the structures.

Test #	Flow path	Structures	Flow geometry	Inj. Flow (ml/min)	Pump flow (ml/min)	Tracer	Distance
C-1	KI0025F03:P5 – KI0023B:P6	20, 21	Forced injection	45	2000	Br-82, S-35, Na-24, K-42, Ca-47, Rb-86, Cs-134, Uranine	14 (16)
C-2	KI0025F03:P7 – KI0023B:P6	23, 20, 21	Forced injection	10	2000	Re-186, Re-188, Ca-47, Ba-131, Cs-137	17 (97)
C-3	KI0025F02:P3 –	21	Passive	–	2000	HTO, Na-22, Sr-85, Rb-83, Ba-133	35 (35)
C-4	KI0025F03:P5 – KI0023B:P6	20, 21	Forced injection	45	2000	HTO, Sr-85, Mn-54, Co-57, Zn-65, Uranine	14 (16)

The results indicate breakthrough of tracer from each of the injections. An example of a breakthrough from injection C1 (#20 → #21) is presented in Figure 3-16. It should be noted that transport here is dominated by Structure #20 resulting in essentially transport along one single structure.

An interesting observation with regards to the Phase C tests is the observed non-breakthrough of Rb (Injection C3) and Cs (injection C2) observed over distances of 30 and 100 m respectively, over a time scale of half a year. In addition, the injection C4 which featured injection of Mn-54, Co-57, Zn-65 shows breakthrough of Mn-54, only slight recovery of Co-57 and no breakthrough of Zn-65, which is in parity with the hypothesis set up beforehand.

In summary, despite minor problems with injection circulation pumps during Phase C, the tests with sorbing tracers in the block scale have been highly successful and constitute a valuable data base on transport and retention in the block scale. However, the underlying data base of tests with conservative tests should not be forgotten. In total, 13 flow paths with full breakthrough over distances ranging between 12–120 m and mean travel times of 1.5 to 2200 hours have been characterised. Of these, at least 4 flow paths show recoveries > 80% (of which three have been used for Phase C tests). Three flow paths with projected distances 35–50 m show no breakthrough (time is a constraint). In conclusion, the possibility to run sorbing tracer tests in the block scale has been successfully demonstrated.

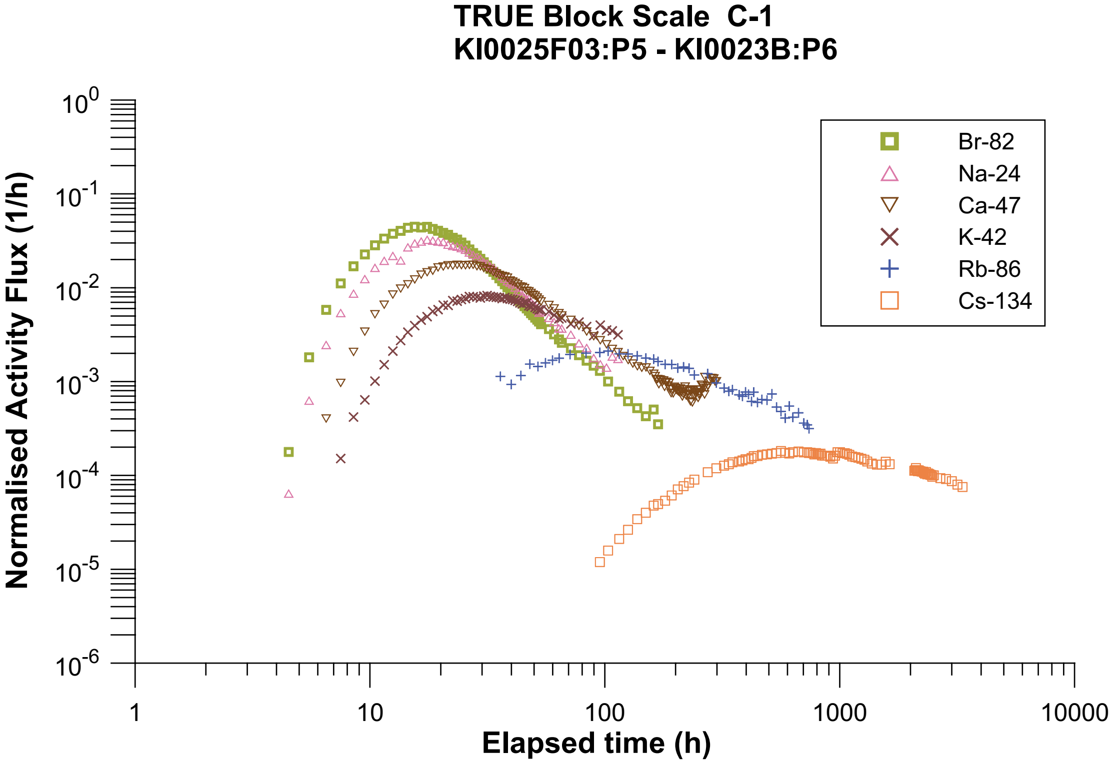


Figure 3-16. Example of breakthrough curves from the flow path. KI0025F03:P5 (#20) to KI0023B:P6 (#21).

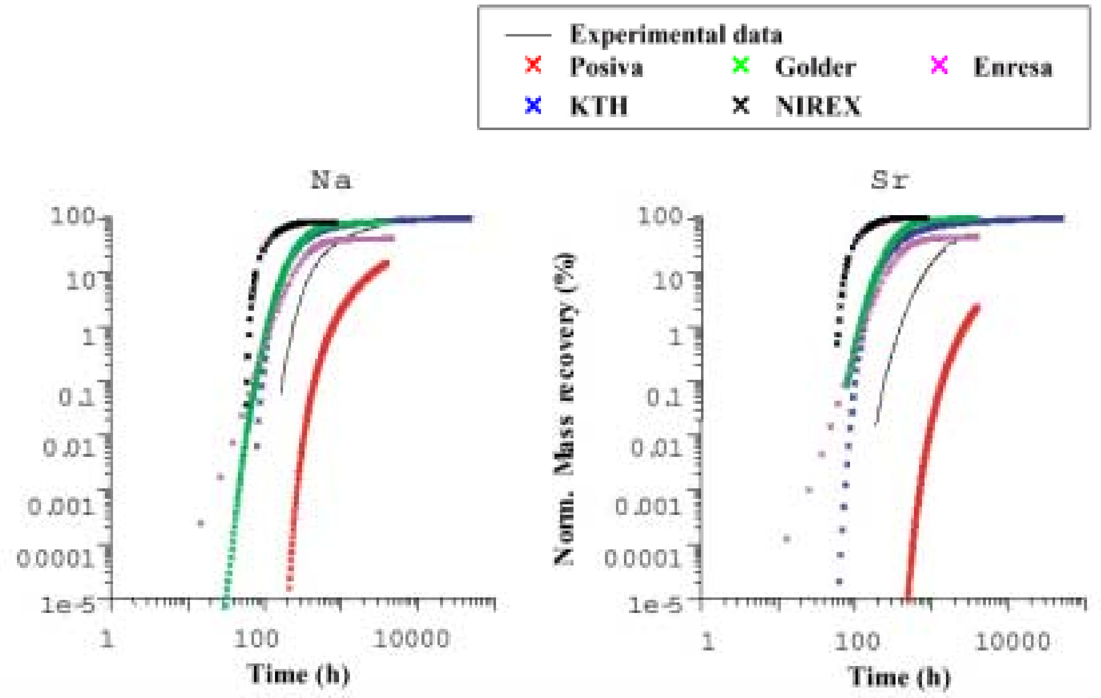


Figure 3-17. *Model predictions of Phase C tracer tests. Example from Injection C2 involving transport over a projected distance of about 100 m.*

Modelling

During the year two more modelling concepts have been included in the palette of various modelling approaches used; the LaSAR approach /Cvetkovic et al, 1999, 2000/ extended to the block scale and the POSIVA approach /Hautojärvi and Taivassalo, 1994/. The work during the year has been devoted to evaluation and calibration of data from the Phase A and Phase B tests, respectively. Following the necessary calibration, the Phase C tracer tests have been predicted using all five modelling approaches, including the Stochastic Continuum (ENRESA), Discrete Feature Network (NIREX) and Pipe Channel Network concepts (JNC/Golder).

In Figure 3-17 the results of model predictions for injection C2 using the various model approach are shown in terms of cumulative breakthrough. In making the predictions the LaSAR and CN approaches have been applying the retention parameters which have been obtained from the evaluation from the TRUE-1 experiment.

Planned work for 2001

- Evaluation modelling of Phase C tracer tests.
- Reporting.
- Continued monitoring of breakthrough at reduced level of ambition (part of TRUE continuation).
- Application of enrichment techniques to detect tracers and provide more data on the tails of the breakthrough (part of TRUE continuation).

3.3.3 Long-Term Diffusion Experiment

Background

The Long-Term Diffusion Experiment is intended as a compliment to the *in-situ* dynamic experiments and the laboratory experiments performed within the TRUE Programme.

The objectives of the planned experiment are to /Byegård et al, 1999/:

- investigate diffusion into the matrix rock from a natural fracture in situ under natural rock stress conditions and hydraulic pressure and groundwater chemical conditions,
- obtain data on sorption properties and processes of some radionuclides on natural fracture surfaces,
- 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.

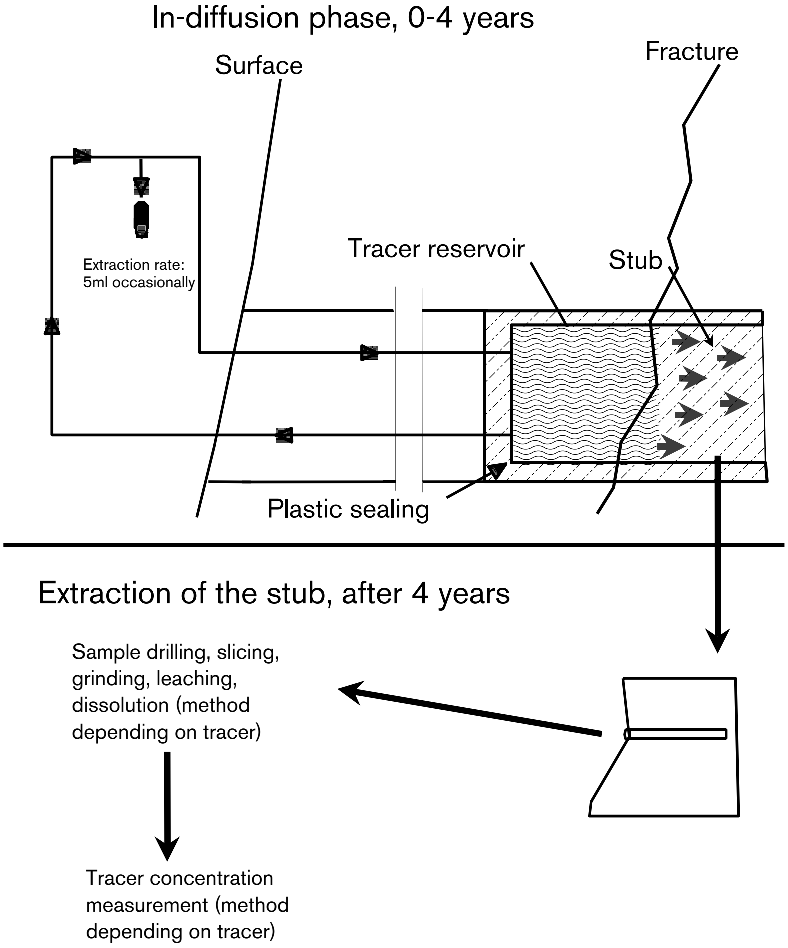


Figure 3-18. Schematic of LTDE experimental concept including injection borehole in contact with a fracture surface, combined with excavation and penetration profile studies.

The updated test plan presents an experimental concept centred on establishment of an experimental (large diameter) borehole which exposes a fracture surface. This fracture surface is packed off with a cap, similar to the one used in the REX experiment, cf Figure 3-18. The intention is to establish an experimental chamber in which a tracer solution is circulated over a period of four years. Performed scoping calculations using available diffusivity data indicates that axial diffusion will range from mm:s for the strongly sorbing tracers to dm:s for the weakly sorbing tracers considered. Apart from tracers used in the TRUE-1 experiment, also PA-relevant tracers (^{99}Tc, ^{237}Np and ^{241}Am) have been proposed. The principal challenge of the experiment is to establish axial diffusion from a natural fracture, through the rim zone of fracture mineralisation and alteration, into the unalterad rock matrix, without any advective flow component (towards the tunnel). This is resolved using a multi-packer system which effectively shields off the gradient. In addition, an intricate pressure regulation system is devised which will effectively allow the pressure in the experiment chamber to adapt to the ambient conditions without causing pressure differences, and hence no advective transport. The reference pressure is obtained either from a packed-off pilot borehole in the immediate vicinity of the large diameter experimental borehole (also used to identify the target fracture to be investigated) or from a conductive guard section adjacent to the test section in the experimental borehole.

The characterisation of the large diameter borehole includes ia. measurements with various geophysical logs (BIPS, resistivity. In addition the core will be analysed using mineralogical, petrophysical and geochemical methods.

Results

Drilling and site characterisation

A suitable target fracture was identified in borehole KA3065A02 at a depth of 9.81 m. This structure constitutes a chlorite splay (141/81) to a main fault, the latter on which slicken lines on the surface are evident. It shows mylonitic character in diorite/greenstone with an increasing alteration towards the fault centre. The total inflow at this zone is about 16 l/min. The target structure constitutes the delimiting structure of the zone and is followed by a long > 0.5 m long intact portion of Äspö diorite.

The drilling of the telescoped experimental borehole (∅ 300 mm) was performed with a high degree of interactivity between; careful iterative drilling in short uptakes (particularly in the inner part of the bortehole), BIPS imaging, core examination and on-site structural modelling/updating of structural model. The original plan was that the target fracture should be intercepted and passed in such a way that an approximately 50 mm long “stub” remained in the borehole. The distance between the mantel surfaces of the pilot and experimental holes at the location of the target feature is about 0.3 m, cf Figure 3-19. However, because of poor visibility due to degassing (which impaired the BIPS imaging) and the fact that a critical segment of one of the final core uptakes fell out of the core barrel, the final core length is about 150 mm.

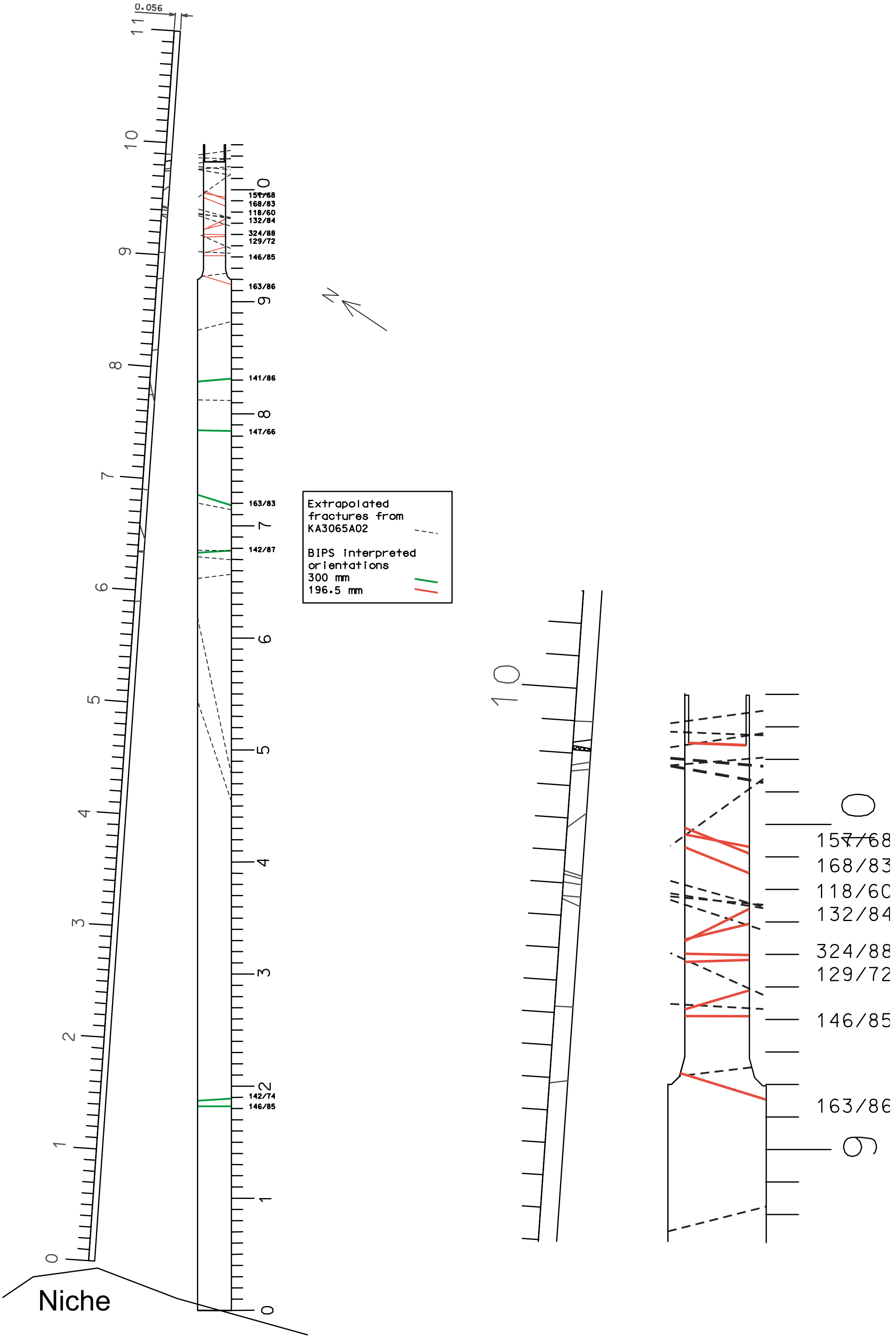


Figure 3-19. *Structural model of the identified fractures and target structure at the LTDE site.*

Structural and geological modelling

Structural modelling of the area around the target feature is still ongoing, supported by detailed structural mapping of the two cores and mineralogical and geochemical analyses. The updating of the hydro-structural model of the LTDE site has been more problematic than anticipated. The problem lies not so much in the linking of the marker structure in the pilot borehole with the target structure in the large diameter borehole. Instead it has been found difficult to link structures/fractures predicted from the pilot borehole with those found in the large diameter experimental borehole. The main problem is interpreted to be associated with scale (smaller structures/fractures) compared to e.g. the structures which have been connected between boreholes at the TRUE Block Scale site, cf Section 3.3.2, in combination with an undulating character in the fractures considered. Detailed mineralogy and geochemistry has in this context helped out in improving the correlation of structures between the two boreholes. The structural model of the LTDE site and the identified target structure is shown in Figure 3-19. An interpretation of the layered structure of the target feature and the division of mineral coating of the surface of the core stub end is shown in Figure 3-20.

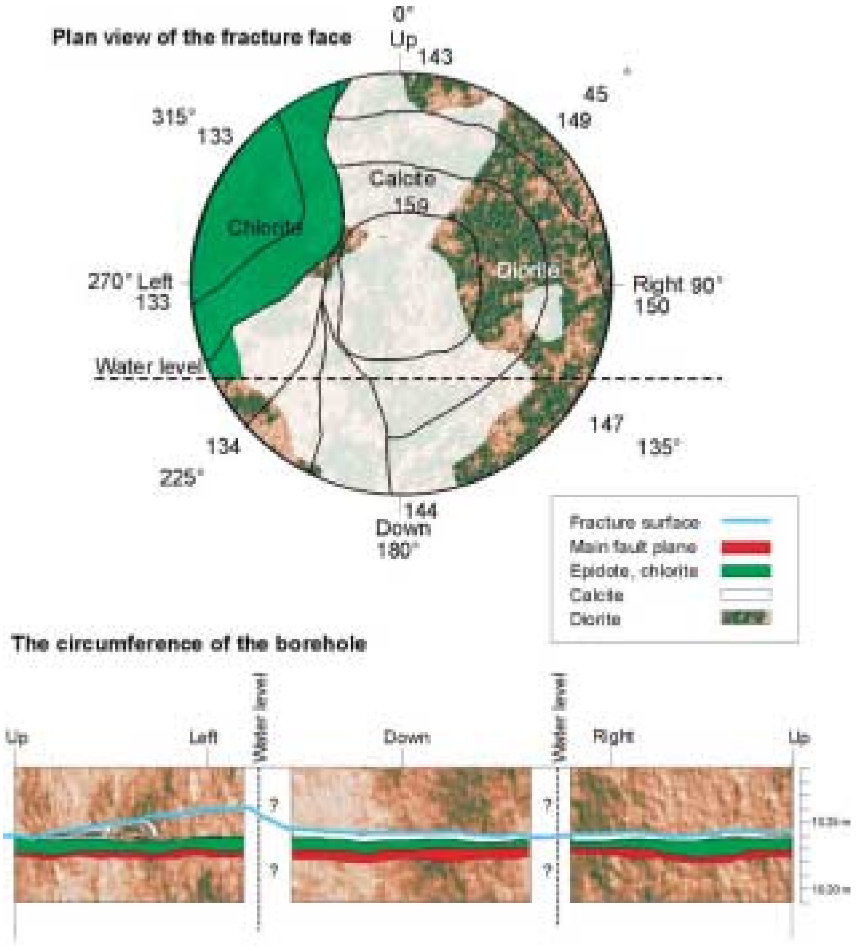


Figure 3-20. *Interpretation of stratigraphy of identified target structure and distribution of fracture coatings on the core stub end.*

Assessment of core stub stature

A pointed out above, the core stub length in KA3065A03 turned out 3 times longer than the originally planned 50 mm.

The implications of this state of affairs are:

1. The projected diffusion length in the core is three times longer than originally planned. The diffusion front for the least sorbtive tracers is expected to be in the order of 0.3–0.4 m, i.e. 50% of the diffusion path of the least sorbing tracers will be in the core stub. The core stub may to a variable degree be affected by sample disturbance due to; (i) stress concentrations associated with the advancing drill bit, and (ii) unloading of stress acting of the remaining core stub.
2. The sealing length of the stub is 150 mm, compared to the originally optimised sealing length of 50 mm. This was originally regarded as a serious constraint, but through design of a sandwiched polyurethane cylinder with successively less deformable material towards the surface of the stub, the problem was resolved.

To investigate the effects noted under item (1) above, a series of in-situ and laboratory measurements have been conducted during the year which have been compared with existing in-situ Äspö data/results and results/data found 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 around the core stub. In addition, the experimental borehole and the stub surface has been documented by analog video mounted on a remote controlled vehicle. The results showed that no macroscopic fractures could be seen on the walls of the stub. Second, the inflow points along the boreholes could be established in a tentative way from the video recordings. 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. The seismic work on a 177 mm core specimen indicate a 2–4% reduction in seismic velocity compared to what is attributed to intact unfractured Ävrö granite. The results of the thin section work show that the mapped fractures are primarily radial (parallel to core axis) and that they diminish in number when moving towards the interior of the core, cf Figure 3-21. The background frequency of micro-cracks in approximately 1 fracture/mm in the interior of the studied 177 mm core, whereas the frequency in the outer 3 mm is in the order of 1.7–3.3 fractures/mm, cf Figure 3-21.

In addition, existing and new rock mechanical modelling has been used to assess the effects of drilling and stress relaxation on the core and its environment. The 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. The degree to which unloading of rock stresses will create significant damage is intimately tied to the in situ state of rock stress conditions at the site. The effect of the unloading in the relatively low-stressed rock at Äspö is expected to be small, the effects in terms of opening of grain boundaries and widening of existing micro fractures is expected to be minimal.

Given that the stub is disturbed and the possibility that diffusion of weakly sorbing species through the stub may not reach the intact rock beyond, has stimulated exploration of alternative concepts. These include division of the experiment in two parts, one

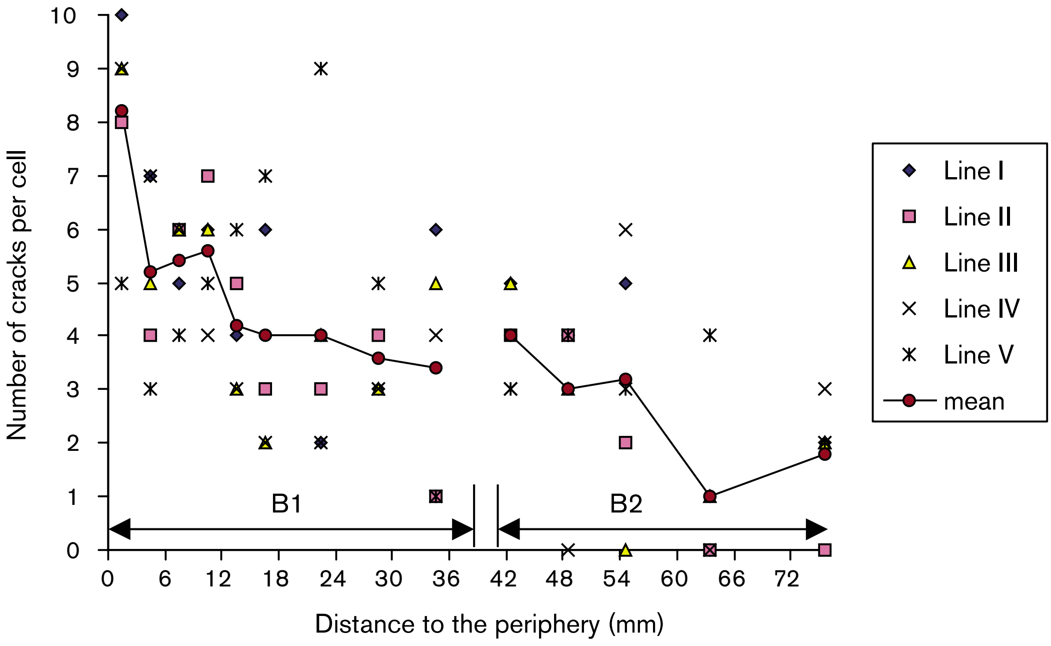


***Figure 3-21.** Number of fractures/cell in samples B1 and B2 vs distance of the measurement cell to the periphery of the 177 mm core (cell size = 3 mm).*

focused on diffusion/sorption on the fracture surface/core stub and one part focused on diffusion in the intact bedrock. The concept being considered most feasible is to assess the intect rock using a small diameter borehole through the centre of the core stub.

Hence, although the geometrical premises for the experiment as originally planned are not fulfilled, the experiment is still doable and relevant, even in light of the insufficiency introduced by the too long stub.

Equipment

During the year the downhole equipment has been finalised. A special installation rack has been constructed with which the packer system will be installed. Further a flow through cell has been manufactured of PEEK which will enable measurement of pH and Eh. Apart from monitoring the redox conditions, further precautions will be taken to avoid exposure to oxygen by hosting all relevant equipment (flow meter, circulation pump, flow meter and pressure regulation piston) in two plexi-glass boxes equipped with gloves and temperature regulation.

CE-marking of equipment set-up

Within SKB work is ongoing on updating quality systems. In addition a general policy decision has been taken that equipment and experimental setups used should be marked with the CE marker, governed by European Union regulations. The CE marker is a signature that the equipment and equipment set up is safe from a personal and functional safety standpoint, and that the risk for environmental hazard is minimised. The LTDE in this context constitutes a training set for SKB. The CE process has had a positive effect on the final phase of the LTDE construction, although it has slowed down the project in relation to the original schedule.

Planned work

Adaption of modified experimental concept. Pre-tests in the array of boreholes by which the connectivity and piezometry of the structures is controlled. Furthermore, various leakage scenarios are tested to demonstrate controlled recovery of tracer in the event the experiment has to be terminated. A permit will be obtained from the radiation protection agency for the pre-tests and the main injection before injections are started.

3.4 The REX-experiment

3.4.1 Background

Molecular oxygen entrapped in a crystalline rock repository after closure is a potential corrodant of the copper in the canisters. Similarly, future intrusions of oxygen-rich melt waters during a glacial event may affect the integrity of the canisters, as well as the migration of radionuclides. The rate of disappearance of O_2 in geological environments is therefore an important information when evaluating repository designs.

A block scale redox experiment was carried out in a fracture zone at 70 m depth in the entrance tunnel to Äspö /Banwart et al, 1996, 1999/. In spite of massive surface water input, the fracture zone remained persistently anoxic. The main conclusion from that study was that the increased inflow of relatively organic-rich shallow groundwater instead of adding dissolved oxygen, it added organic compounds that acted as reductants in the deeper parts of the fracture zone. These conclusions are specific to this particular fracture zone, experimental conditions and the time scale (3 years) of the experiment, but are probably also relevant for other conductive fracture zones.

The detailed scale redox experiment (REX) was started to focus on the question of O_2 that is trapped in the tunnels when the repository is closed. The aims of the experiment were to determine:

- How does oxygen trapped in the closed repository react with the rock minerals in the tunnel and deposition holes and in the water conducting fractures?
- What is the capacity of the rock matrix to consume oxygen?
- How long time will it take for the oxygen to be consumed and how far into the rock matrix and water conducting fractures will the oxygen penetrate?

3.4.2 Experimental concept

The emphasis of the project was on a field experiment involving groundwater in contact with a fracture surface /Puigdomenech et al, 1998, 2000b/. To this aim a borehole, ≈20 cm in diameter, was drilled at 380 m depth in the tunnel of the Äspö Hard Rock Laboratory. Fe-carrying phases in the fracture surface were chlorite, clay minerals, epidote and pyrite. Injection pulses of O_2 dissolved in groundwater were performed at in situ temperature and pressure. Several microbial and chemical parameters were determined as a function of time: pH, Eh, and O_2-concentration, microbial counts and activities, and structure of microbial populations. The set-up for the REX field experiment is illustrated in Figure 3-22.

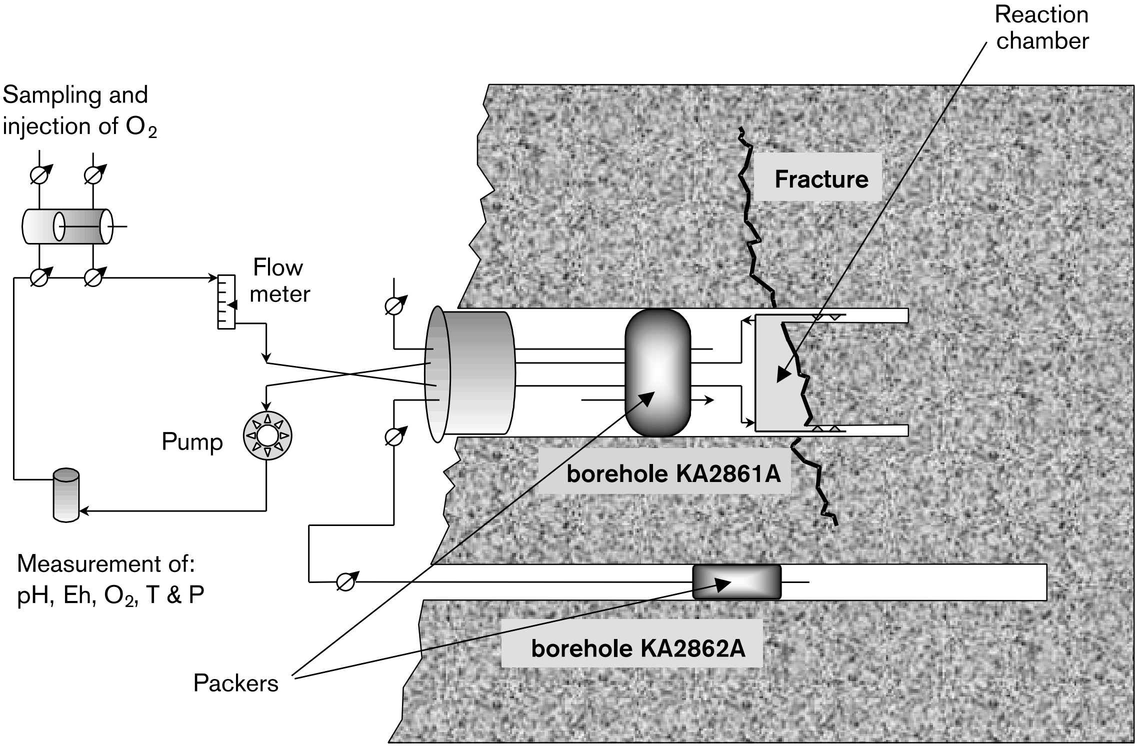


***Figure 3-22.** Schematic illustration of the REX field experiment.*

The field study was supported by laboratory experiments to determine O_2 reaction rates and mechanisms with Äspö samples (both for inorganic and microbially mediated processes). A replica experiment was performed at CEA Cadarache, France, with the other half of the fracture surface obtained in the drilling procedure of the in situ experiment. The aim of the replica experiment was to duplicate as far as possible the conditions of the REX in situ experiment, for example by using groundwater sampled at the REX site in Sweden, shipped in special containers to France.

3.4.3 Results

Four laboratory groups participated in the REX-experiment: the Dept. of Civil & Environmental Engineering of the University of Bradford (UK); the Fluid Processes Group of the British Geological Survey (UK, financed by PNC, Japan); the Centre d'Etudes Nucléaires Cadarache (France, financed by ANDRA); and the Dept. of General and Marine Microbiology of the Göteborg University. Additionally several consultants in Sweden participated in the project /Puigdomenech et al, 1998/.

Supporting Laboratory Investigations

Laboratory experiments performed at Bradford University tested the O_2 uptake by rock and fracture filling mineral samples collected from the Äspö tunnel. Fracture-filling minerals were also collected from the NW-3 fracture zone using the "triple tube" technique in a 3 m long borehole (KA3065A). The core from this borehole was characterised and the sieved fractions were also used in the laboratory tests at the University of Bradford. Oxygen uptake rates were determined for most of the samples /Puigdomenech et al, 2001/. The results obtained showed that the rate of O_2 uptake is affected by particle size of the samples and by their origin in the Äspö tunnel (variation in mineral composition and degree of alteration). The values of the first-order rate constant obtained are in the range (1 to 140) × 10^{-3} L g^{-1} day^{-1}.

Dissolved gases (CH_4, H_2, etc) were analysed in Äspö groundwaters /Kotelnikova and Pedersen, 1999/, and the data were combined with the measurements of microbial O_2 reduction and CO_2 production in Äspö groundwaters. These results showed that O_2 may be consumed by methanotrophic, hydrogen-oxidising or heterotrophic bacteria in a closed nuclear waste repository. The results on bacteriological O_2 consumption experiments performed in the field at Äspö are given elsewhere /Kotelnikova and Pedersen, 1999/. Monod-type kinetic rate laws were used to calculate the time scale to consume O_2 in a closed repository /Kotelnikova and Pedersen, 1999, 2000; Puigdomenech et al, 2001/. The results showed that an initial oxygen content of $[O_2]_o = 8$ mg L^{-1} (0.25×10^{-3} mol L^{-1}) would be consumed by microbial processes in the groundwater to levels below 0.1% in one year.

The Japan Nuclear Cycle Development Institute (JNC) and the British Geological Survey (BGS) jointly studied the microbial effects on redox groundwater-rock interactions using samples from Äspö. Detailed results from these laboratory investigations were reported elsewhere /Bateman et al, 1998; Yoshida et al, 1999/. Both batch and flow experiments were performed. Biofilm development was observed in the column experiments. The columns with bacteria became clogged very rapidly, and minor amounts of smectite were observed in the reaction residues examined after this period (about two weeks). Experiments without bacteria did not clog up. These results are consistent with bacterially enhanced smectite formation being responsible for the clogging of the column experiments /Bateman et al, 1999; West et al, 2001/.

The In-Situ Experiment

The REX field experiment was conducted on a single fracture at 8.8 m from the tunnel wall (borehole KA2861A, ∅ ≈ 200 mm). The drillcore was sent to CEA (Cadarache, France) where the replica of the field experiment has been completed as described below.

The aim of the field study was to isolate the innermost part of the borehole and to monitor the uptake of O_2 as a function of time. A detailed description of the set-up for the REX field experiment has been reported /Puigdomenech et al, 1998/, and it is summarised in Figure 3-22.

A series of O_2 injection pulses were performed in the REX in situ (and replica) experiments. Dissolved oxygen concentrations in the range 1–8 mg L^{-1} were consumed in the experiments within a few days, 5 to 10 days. Data for one of the O_2-pulses is shown in Figure 3-23. The data could be described with a first order kinetic equation. Further refinements of the rate law were not possible owing to the limitations of the field experiment, mainly: hydraulic leakage through microfractures and o-rings, and diffusion of atmospheric O_2 into the reaction loop /Puigdomenech et al, 2000a, 2001/.

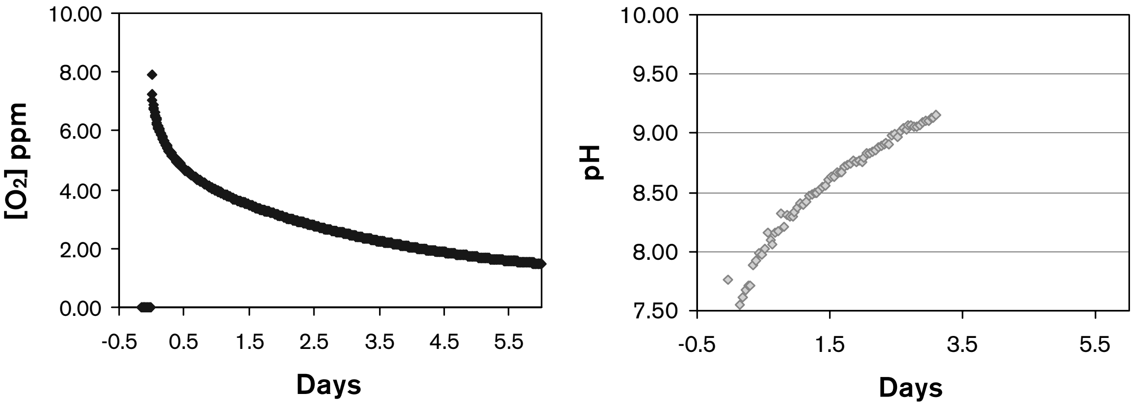


Figure 3-23. *Results from one of the O_2-pulses in the REX field experiment.*

Microbial data from the in situ experiment showed O_2-induced aerobic microbial respiration and a succession of microbial groups in the groundwater and on mineral surfaces /Kotelnikova and Pedersen, 2000/. It was unexpectedly found that in some cases the number of iron-reducing organisms increased during the O_2 pulses. Similar effects were observed in the replica experiment. It appears that iron-reducing bacteria developed because of the increased Fe(III) concentrations that followed the O_2 pulses.

The number of cells attached as biofilms exceeded the number of free-living cells. These biofilms would potentially lead to changes in the absorbing properties of the mineral surfaces. The O_2 uptake capacity of the rock is therefore largely affected by the microbial films developing in fracture surfaces.

The replica experiment

As part of the REX project, ANDRA and CEA performed a laboratory experiment that reproduced closely the field test, i.e. a study in which a diorite core section was submitted to the same succession of O_2 injections as in the field experiment. The use and purposes of such an experiment, called the replica experiment, were both methodologic (how to dimension and complement the in situ experiment) and scientific (gathering more data and better understanding of processes). The small spatial extension of the in situ reaction chamber was especially suitable for a replica investigation. The replica experiment was performed on the other half of the fracture surface used in the field experiment. The replica set-up was designed in order to work at a total pressure of 1 bar; different tests and preliminary investigations guided the choice of materials for the different parts of the set-up: core confinement unit, measurement unit, water equilibration unit, tubes and fittings /Puigdomenech et al, 1998, 2001/. The replica experiment started in June 1998 and ended in May 1999. During this period, O_2 pulses of increasing intensity were injected and different parameters were monitored (especially O_2(aq), pH, Eh, solution chemistry, microbial populations). There were long anoxic periods between series of O_2 pulses in order to follow the progressive return to reducing conditions.

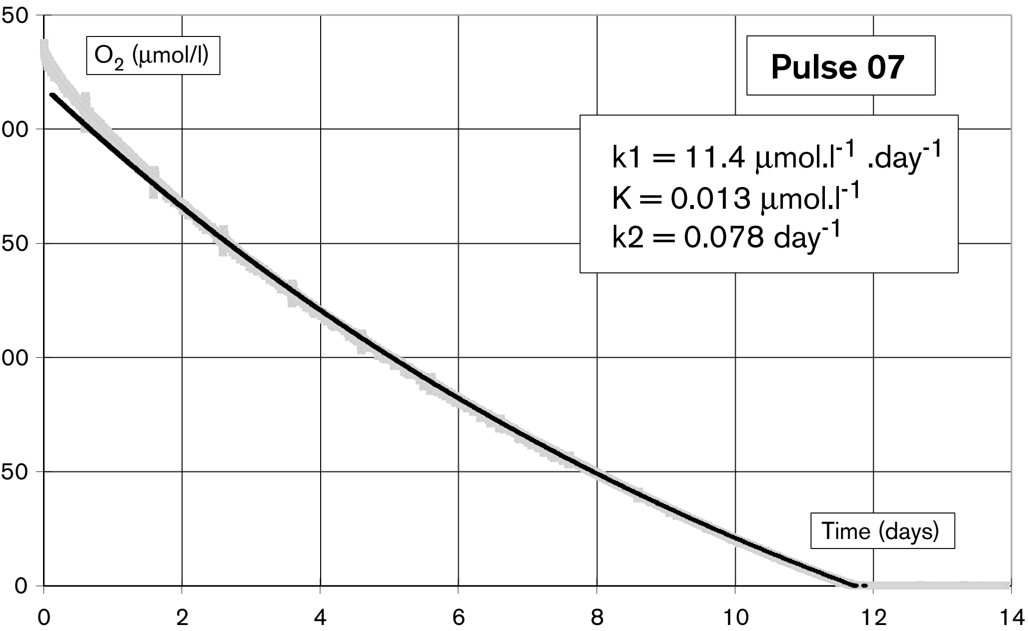


Figure 3-24. *Time evolution of dissolved* O_2 *during a pulse in the replica experiment. The observed evolution is compared to a curve calculated using a combination of first rate law and enzymatic catalysis (monod law for microbial processes).*

It was observed that the oxygen uptake kinetics could be fairly simulated by a rate law combining both Monod kinetics (enzymatic kinetics) and a first order contribution (Figure 3-24). The form of this rate law was:

$$\frac{d[O_2]}{dt} = -\frac{k_1[O_2]}{K+[O_2]} - k_2[O_2]$$

the values for k_1, K and k_2 were found to be respectively 5–20 µmol L^{-1}day^{-1}, 0.05–0.50 µmol L^{-1}, and 0.04–0.10 day^{-1}. During periods of oxygen uptake, the pH was observed to decrease regularly. After O_2 depletion, the pH increased back and a rapid drop of Eh (measured using a Pt electrode) was observed. Upon addition of successive O_2 pulses, the carbonate alkalinity of the water increased progressively. This feature was consistent with the succession of major bacterial groups (aerobes, anaerobes and iron-reducing bacteria). During long anoxic periods, the iron and manganese concentrations in solution increased strongly, consistently with the continuous drift of Eh to lower values (typical values attained in three months were Eh = –0.05 V_{NHE} for pH about 6.2 at 15°C). At the end of anoxic periods, a strong growth of sulfate reducing bacteria was observed. A coupling between mineral/solution/bacterial interaction is strongly suggested both in the replica and in situ experiments.

3.4.4 Main Conclusions from the REX Project

The most important conclusions from the REX project are (Puigdomenech et al, 2001):

- O_2 uptake rates in the field were comparable to laboratory results obtained in France and UK.
- Previous laboratory O_2 uptake rates by mineral samples /White and Yee, 1985/ and results from the URL in Canada /Gascoyne, 1997/ resulted in expected time scales for O_2 depletion in typical granite fractures between 0.2 and 350 years. The data collected within the REX project results in calculated time scales for oxygen uptake in granitic fractures that are on the order of a few days.
- Microbes had a substantial role in O_2 uptake, both in biofilms and in unattached state. The microbial processes were apparently coupled to reactions at mineral surfaces through iron or manganese cycling (e.g., by fast chemical oxidation of Fe(II) in solution, and consequent microbial reduction of Fe(III) by iron-reducing bacteria).
- A substantial reducing capacity should be assigned to CH_4 and H_2, which diffuse from deep geological sources. These compounds may be used by microbes as a redox buffer against the intrusion of O_2-rich waters, independently of surface climatic conditions, i.e. even under glacial periods.

3.5 Radionuclide retention (include CHEMLAB)

3.5.1 Background

The retention of radionuclides in the rock is the most effective protection mechanism when the engineered barriers fail and radionuclides are released from the waste form. The retention is mainly due to the chemical properties of the radionuclides, the chemical composition of the groundwater, and to some extent also due to the conditions of the water conducting fractures and the groundwater flow.

Laboratory studies on the solubility and migration of long lived nuclides of e.g. the elements 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. In such a case the migration of the nuclides, released from a waste containment, will stop as soon as the source term is ending.

Laboratory studies have been undertaken with this kind of nuclides even though natural conditions are extremely difficult mimic. Although experiences from different scientists are uniform it is of great value to demonstrate that results from laboratory studies are valid under natural conditions. Laboratory investigations have difficulties to simulate these conditions and may therefore be dubious as validation exercises. The CHEMLAB borehole probe has been constructed and manufactured for validation experiments in situ at undisturbed natural conditions. Figure 3-25 illustrates the principles of the CHEMLAB 1 and CHEMLAB 2 units.

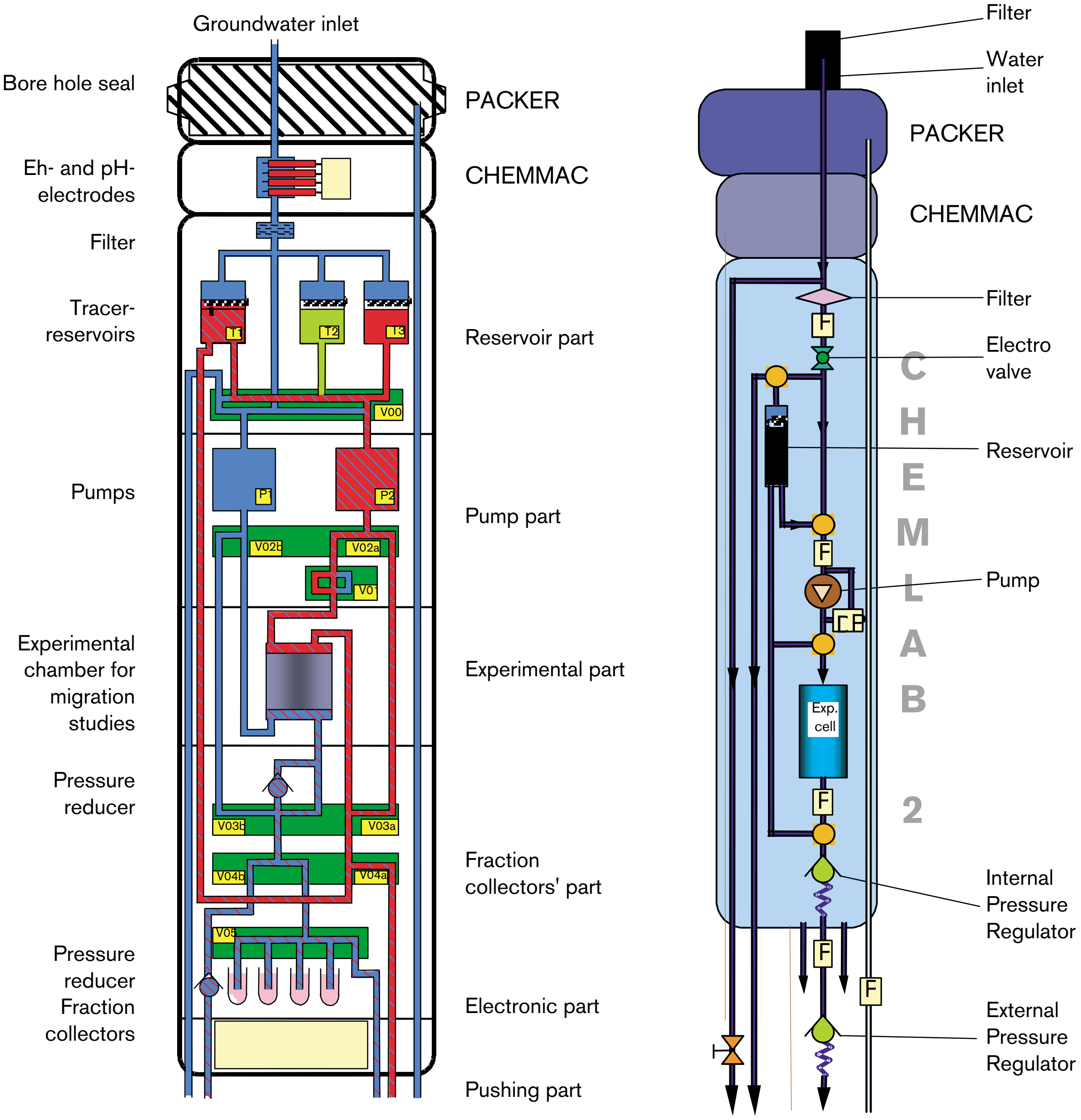


***Figure 3-25.** Schematic illustration of CHEMLAB 1 and 2.*

3.5.2 Objectives

The objectives of the Radionuclide Retention (CHEMLAB) experiments are:

- To validate the radionuclide retention data obtained in laboratory experiments by data from in situ experiments in the rock.
- To demonstrate that the laboratory data are reliable and can be used to predict the behaviour of radionuclides at conditions prevailing in the rock.
- To decrease the uncertainty in the retention properties of relevant radionuclides.

3.5.3 Experimental concept

CHEMLAB is a borehole laboratory built into a probe, in which migration experiments can be carried out under ambient conditions with respect to pressure and temperature with the use of natural groundwater from the surrounding rock.

Initially one "all purpose" unit was constructed in order to meet a wide range of expected experimental requirements. This unit CHEMLAB 1 has been used for the "diffusion in bentonite" /Jansson and Eriksen, 2001/ experiments and will now be used for similar experiments including the effects of radiolysis. Others to follow are:

- Migration from buffer to rock.
- Desorption of radionuclides from the rock.
- Batch sorption experiments.

The CHEMLAB 2 unit is a simplified version of CHEMLAB 1, designed to meet the requirements by experiments where highly sorbing nuclides are involved. These are:

- Migration of redox sensitive radionuclides and actinides.
- Radionuclide solubility.
- Spent fuel leaching.

3.5.4 Results

Cations

During spring and summer 1997 the first radionuclide in-situ experiments with CHEMLAB were performed at Äspö HRL. These included cation diffusion in compacted bentonite with the tracers Co-57, Sr-85 and Cs-134. The experiments were carried out, partly to gain experience in the novel experimental technique, but mainly to validate diffusion and sorption data obtained in laboratory experiments.

The selected nuclides are expected to exist predominantly as non-hydrolysed cations that are not influenced by pH or Eh. Cs^+ and Sr^{2+} have been extensively studied in laboratory and the diffusive and sorptive properties are reasonably well known /Eriksen and Jansson, 1996; Yu and Neretnieks, 1997; Muurinen, 1994/. Of critical importance for their sorption and diffusion in bentonite is the concentration of major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}) and for Sr^{2+} also the pH.

The sorptive and diffusive properties of Co^{2+} are less well known, but Co^{2+} is primarily sorbed by surface complexation and/or surface precipitation on the montmorillonite and pH is of critical importance in the pH-range 7 to 10 /Eriksen et al, 1999/.

Two experiments were performed, the first with Co-57 and the second with Sr-85 and Cs-134. The radionuclides were added in their ionic form (Co^{2+}, Sr^{2+} and Cs^+) to a reservoir in CHEMLAB in a 5 ml solution of degassed, filtered Äspö ground water. The first step in the experiments was to dilute this stock solution to 100 ml with ground water directly from the rock. In the Co^{2+} experiment the 5 mm thick bentonite clay was then equilibrated with ground water from both ends of the cell for 14 days. The tagged Co^{2+} solution was then circulated at the front end of the cell, while the back end was flushed to the fraction collectors of CHEMLAB in intervals to remove and collect all radionuclides that had diffused through the cell.

In the Sr^{2+}, Cs^{+} experiment a 10 mm long cell was used. After diluting the radionuclide solution, the bentonite clay was equilibrated with ground water from one side of the cell. The filter at the front end of the cell was in contact with a solution of constant radionuclide concentration, while the back end was blocked, allowing the radionuclides to diffuse into, but not through, the cell.

To measure the concentration profiles in the bentonite, the cell was dismantled at the end of the experiments and the bentonite cut into thin sections. Each section was weighted and the activity measured by γ-counting using a germanium detector and multichannel analyser. The concentration profiles in the bentonite were simulated using a finite difference based computer code ANADIFF /Eriksen and Jansson, 1996/. The cobalt results were modelled by using a computer code, LFD, developed by Lehikoinen /Pusch et al, 1999/.

The measured and calculated concentration profiles for Cs^{+}, Sr^{2+} and Co^{2+} are plotted in Figure 3-26, Figure 3-27 and Figure 3-28. It should be pointed out that the measured Co^{2+} profile is expected to be somewhat low at the inlet/bentonite interphase due to a pump failure after 8 days diffusion.

The K_d and D_a values used in the computer simulations for the cations are given in Table 3-2. For comparison expected K_d values for Cs^{+}, Sr^{2+} obtained by regression analysis of sorption data from experiments with solutions and groundwaters with different salinity /Eriksen and Jansson, 1996/ as well as apparent diffusivities are also given in Table 3-2. The corresponding Co^{2+} values obtained in our laboratory are also given in the table.

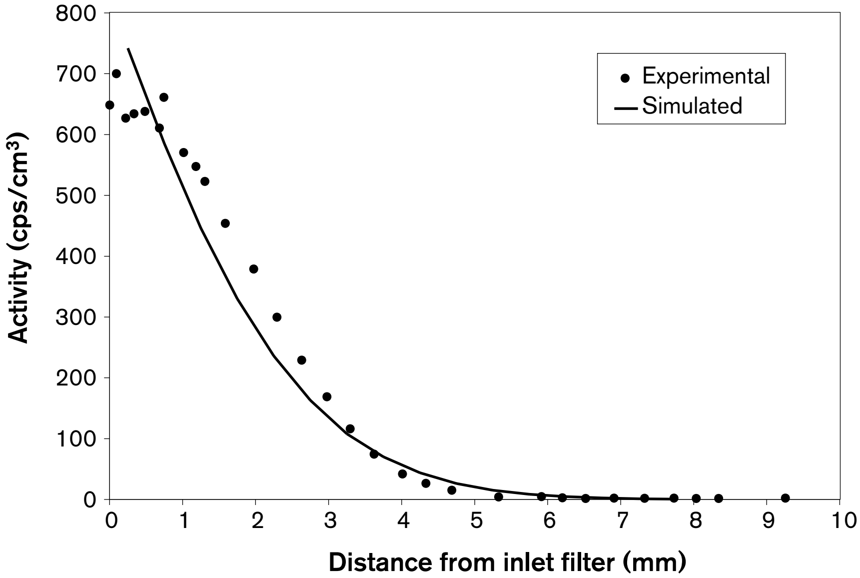


Figure 3-26. *A measured and simulated activity profiles for* Cs^{+} *in bentonite. Diffusion time 15 days,* $D_a = 2 \cdot 10^{-8}\ cm^2\ s^{-1}$, $K_d = 60\ g\ cm^{-3}$.

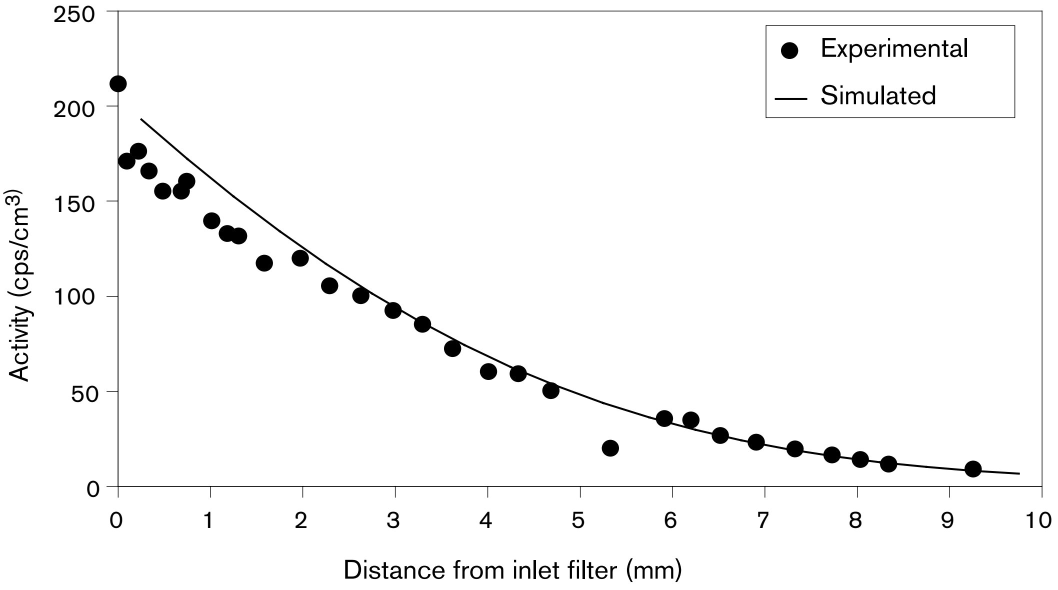


Figure 3-27. *Measured and simulated activity profiles for* Sr^{2+} *in bentonite. Diffusion time 15 days,* $D_a = 7 \cdot 10^{-8}$ cm^2 s^{-1}, $K_d = 13$ *g* cm^{-3}.

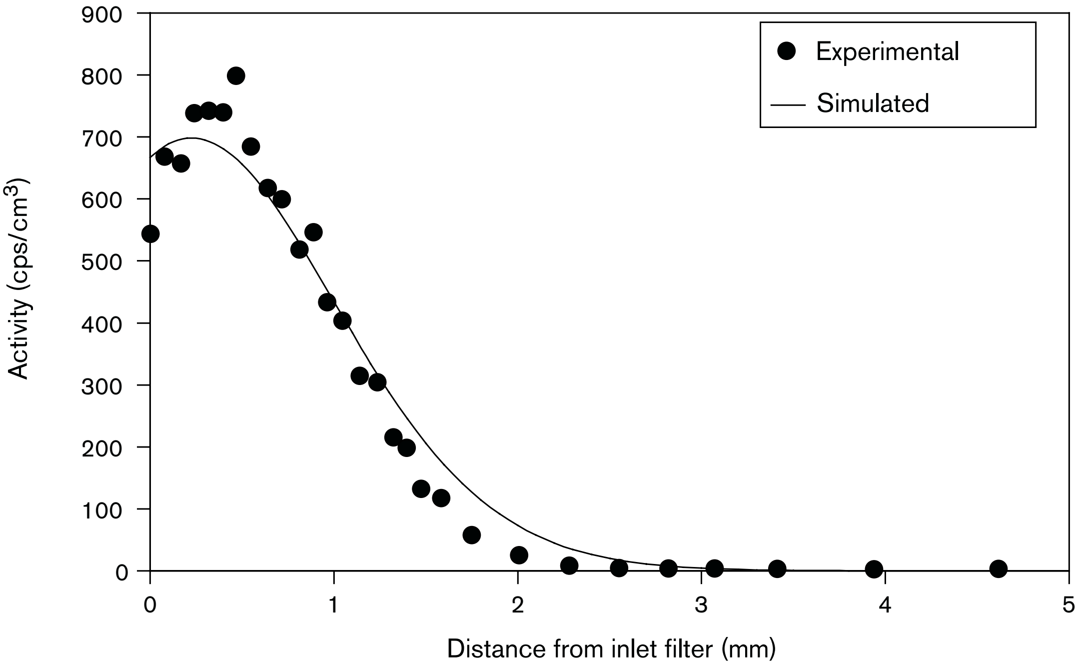


Figure 3-28. *Measured and simulated activity profiles for* Co^{2+} *in bentonite. Diffusion time 8 days with constant inlet concentration and 7 days without continuous replenishment of radiotracer at the inlet side,* $D_a = 4 \cdot 10^{-9}$ cm^2 s^{-1}, $K_d = 250$ *g* cm^{-3}.

Table 3-2. K_d values and apparent diffusion coefficients from CHEMLAB and laboratory experiments.

Cation	CHEMLAB experiments		Laboratory experiments	
	Log K_d [cm^3 g^{-1}]	D_a [cm^2 s^{-1}]	log K_d [cm^3 g^{-1}]	D_a [cm^2 s^{-1}]
Cs^+	1.8	$2 \cdot 10^{-8}$	2 ± 0.35	$(2 \pm 1) \cdot 10^{-8}$
Sr^{2+}	1.1	$7 \cdot 10^{-8}$	1.56 ± 0.32	$(9 \pm 1) \cdot 10^{-8}$
Co^{2+}	2.4	$4 \cdot 10^{-9}$	3.3 ± 0.3	$(2 \pm 1) \cdot 10^{-9}$

The results of the downhole experiments with Sr^{2+} and Cs^+ are in good agreement with results from laboratory experiments with sodium bentonite compacted to 1.8 g cm^{-3} dry density and equilibrated with synthetic groundwater and electrolyte solutions of the same salinity as Äspö groundwater. It ought to be pointed out that the Sr^{2+} concentration in the Äspö groundwater is fairly high (~$2 \cdot 10^{-4}$ mole/l) so the Sr^{2+} sorption observed is really isotope exchange between sorbed Sr^{2+} and Sr^{2+} in the porewater in an equilibrated system.

The difference between the K_d values for Co^{2+} obtained in laboratory diffusion experiments with a synthetic Äspö groundwater is most probably caused by a slightly higher pH of the synthetic groundwater (pH ~7.5) used in the laboratory experiments than of the groundwater at the experimental site at Äspö (pH 7.2). Co^{2+} displays a sorption edge at pH ~6.5 with K_d increasing by two orders of magnitude between pH 6.5 and 8.5. Corresponding sorption edges on Na-montmorillonite for Ni, Zn and Ca have been modelled assuming the formation of surface complexes /Bradbury and Baeyens, 1995/.

Anions

I^- and Tc(VII), probably occurring as pertechnetate, TcO_4^-, were chosen. The choice of anions were based on the following criteria:

- Diffusion behaviour at different chemical conditions should be well characterised.
- Two ions with different redox behaviour should be studied, one which is conservative and one which is redox sensitive.

The transport capacity of iodide has been found to be increasing with increasing ionic strength of the groundwater used, due to anion exclusion, which is ionic strength dependent. In earlier studies using saline synthetic groundwater (NASK, ionic strength = 0.218 molal) the apparent and effective diffusivities were found to be $(9.2 \pm 1.3) \cdot 10^{-7}$ and $(7.0 \pm 1.7) \cdot 10^{-8}$ cm^2 s^{-1}, respectively /Eriksen and Jansson, 1996/.

Technetium is a redox sensitive radionuclide. In an oxidising environment technetium occurs as pertechnetate ion (TcO_4^-), which has been found to be as mobile as the iodide ion. Under reducing conditions the thermodynamically favoured state is $TcO_2 \cdot nH_2O(s)$. However, it has been shown that the reduction of TcO_4^- by Fe(II) proceeds very slowly if at all in free solution, while when sorbed to a surface or precipitated as $Fe(OH)_2(s)$ or $FeCO_3(s)$ the rate for reduction by Fe(II) is significantly faster /Cui and Eriksen, 1996a,b/.

Figure 3-29 displays the concentration profile for I^- and three simulated curves.

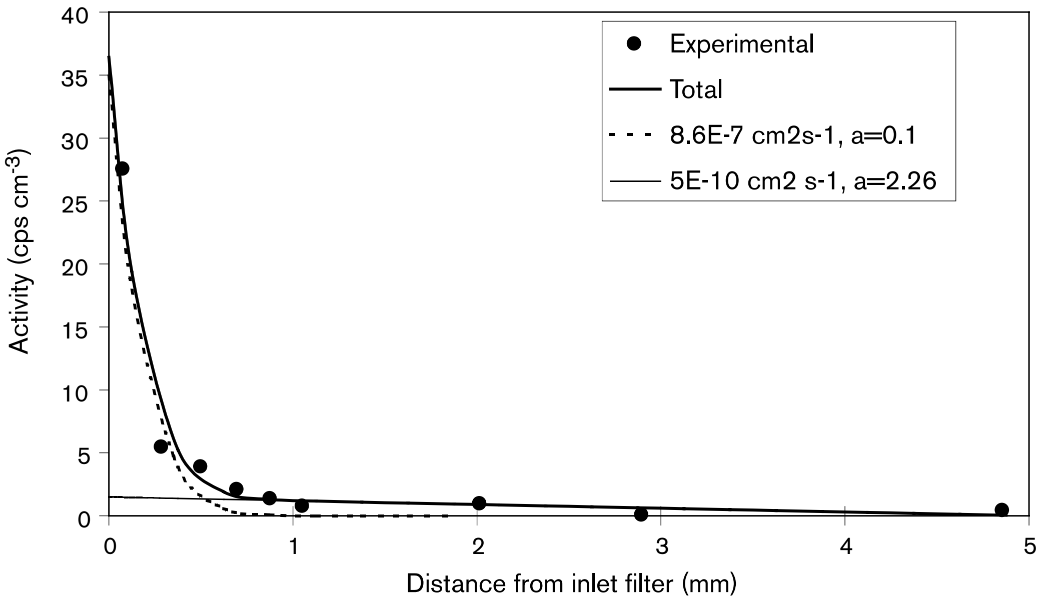


***Figure 3-29.** Experimental and simulated results for iodide.*

The profile for I^- cannot be accommodated by ion exclusion and one diffusion process only. The non-linearity of the profile has been observed at steady-state in earlier investigations /Eriksen and Jacobsson, 1981/ both for iodide and chloride.

The profile can, however, be modelled with two processes. One with anion exclusion and one slower with slight sorbtion. Further laboratory investigations are needed to clarify the behaviour of iodide and similar ions.

In Figure 3-30 the profile for technetium can be seen.

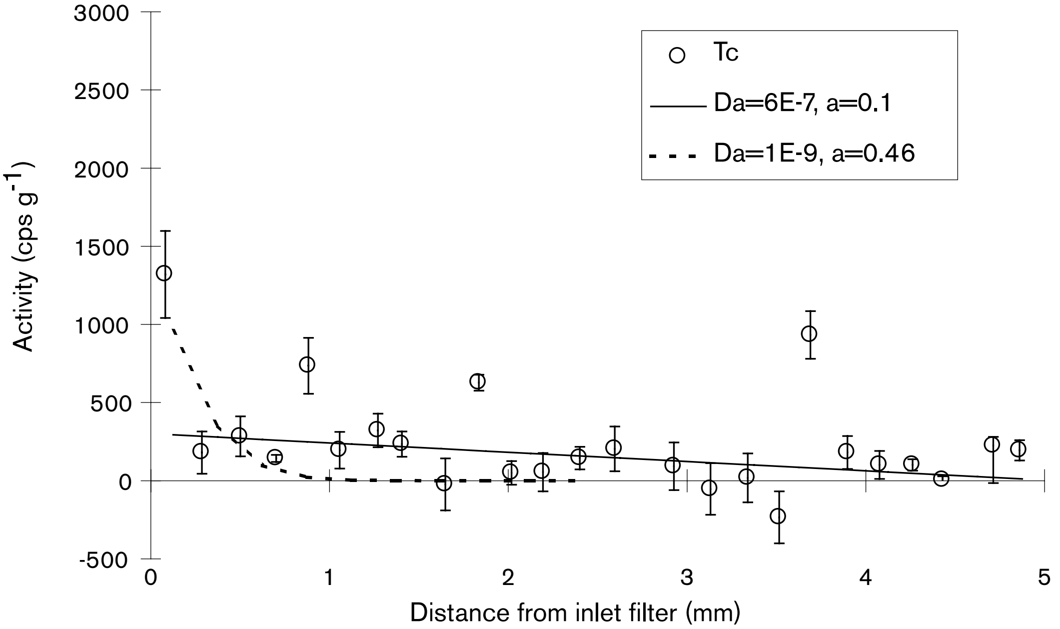


***Figure 3-30.** Experimental and simulated results for technetium.*

The activity level of the Tc-99 profile indicates diffusion of the species TcO_4^-. The high activity spots are probably due to reduction of TcO_4^- by iron containing minerals in the clay.

Migration of Actinides

The first experiment carried out in CHEMLAB-2 was the migration of actinides, americium, neptunium and plutonium, in a rock fracture. Pre-studies performed at Institut für Nukleare Entsorgung at Forschungszentrum Karlsruhe indicates that Pu and Am are sorbed strongly, whereas sorption of Np shows a significant kinetic due to reduction of Np(V) to Np(VI) /Vejmelka et al, 2000/.

During fall of 2000 INE carried out a first of several actinide migration experiments at Äspö in cooperation with SKB staff and Nuclear Chemistry at the Royal Institute of Technology. The rock samples will be analysed with respect to the flow path and to the actinides sorbed onto the solid material. Nondestructive and destructive techniques will be applied, such as x-ray computer tomography and cutting the samples after injection of fluorescent epoxy resin. 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. The analysis are yet not completed.

3.6 Degassing and two-phase flow

3.6.1 Introduction

Two-phase flow conditions, i.e. a mixed flow of gas and water, may develop in the vicinity of a repository situated in a regionally saturated rock mass. The main sources of two-phase flow conditions are 1) gas generation in the repository due to corrosion or biological processes, 2) exsolution of gas (bubble generation) due to pressure decrease, and 3) entry of gas (air) into the rock mass from ventilated tunnels. The presence of a gas phase in the repository before and after closure must be understood in relation to its effect on repository performance. Waste-generated gas may affect repository integrity and hazardous material may be transported in the gas phase.

Understanding evolution and characteristics of two-phase flow conditions near drifts is essential for interpreting observations of hydraulic conditions in drifts, interpretation of experiments performed close to drifts, and performance of buffer mass and backfill, particularly during emplacement and repository closure.

The objectives for the project on degassing and two-phase flow are:

- To show if degassing of groundwater at low pressures has significant effects on measurements of hydraulic properties in boreholes and drifts.
- To study and quantify other processes causing two-phase flow near excavations such as air invasion due to buoyancy and evaporation.
- To show under what conditions two-phase flow will occur and be significant. Conditions expected to be of importance are gas content, chemical composition of groundwater, fracture characteristics (aperture distribution and transmissivities), and flow conditions.

- To get an idea of the time scales required for resaturation of a repository.
- To develop technology for measurement of saturation.

During 2000, the results and conclusions achieved in the SKB degassing and two phase flow project were summarised in a final technical report (currently in review). The achievements include both original development of predictive models, as well as testing of these models and actual use of them for investigation the practical implications of degassing and two-phase flow in general for the hydraulic properties of deep bedrock. In the sections below, the main results and conclusions presented in this report are summarised.

3.6.2 Two-phase flow

In order to address the project objectives, quantitative two-phase flow models are needed. Generally, constitutive relations between capillary pressure, (gas/water) saturation degree and relative permeability provide an important basis in quantitative two-phase flow modelling. However, traditional constitutive relations for unsaturated flow in porous media (e.g., the Brooks – Corey and van Genuchten relations) are based on parameters that can readily be estimated in soil, but are difficult or impossible to determine independently in fractured rock. Therefore, the predictive capability of such typical soil constitutive relations is limited for rock fractures under field conditions, although several studies have indicated that they can be calibrated to reproduce observed unsaturated fracture flow behaviour.

An alternative, fracture aperture based, relation for two-phase flow was preented. The relation is based on properties (the mean aperture and the aperture standard deviation), for which undisturbed field estimates can be obtained through the resin injection technique. Since there are no previous comparative studies for this alternative fractured rock relation, it was compared with the widely used van Genuchten relation for unsaturated flow in porous media. The results showed that both relations yield the same kind of unsaturated flow behaviour, given a wide range of (realistic) parameter values. As discussed above, the van Genuchten relation has been proven useful for calibrated reproduction of unsaturated fracture flow. The consistent result of the comparison implies that the novel fractured rock relation is at least equally capable of calibrated reproduction of unsaturated fracture flow as the van Genuchten relation. Moreover, due to the fact that it is based on parameters that are physically relevant and independently measurable in rock fractures, it has the potential of independent prediction capabilities, which is not the case with the porous medium relations. For the special case of groundwater degassing, this fractured rock relation was developed further, and directly compared with the predictions of the developed relations with the actual outcome of both laboratory and field experiments.

Whereas groundwater degassing is primarily expected to occur relatively close to open boreholes and drifts, where detailed information on fracture aperture properties in principle can be obtained, other multiphase processes that can potentially affect the performance of deep repositories may take place at much larger scales. For instance, for the scenario of gas generation in the repository and subsequent transport through the fractured rock, the relevant scale can be on the order of a kilometre. On this scale, the hydrologic conditions cannot be known in detail throughout the domain. Rather, detailed information will be available in a finite number of sampling locations. This point information then needs to be interpreted in some way that is relevant for the large-scale problem. On basis of the Leverett-scaling procedure for characteristic curves in porous media, a corresponding procedure for the fracture aperture based characteristic curves was developed, and the applicability of this procedure investigated. More specifically, the relevance of using a characteristic curve obtained in a subregion of the model domain (through detailed measurements) was investigated and this curve was scaled based on "soft" data, i.e., some information on the fracture transmissivity distribution in other subregions, in order to obtain characteristic curves for the latter subregions. The results showed that the errors associated with the proposed scaling procedure were small for fractures of different mean apertures, as long as the aperture standard deviations were similar. The method was furthermore exact for fractures with different mean apertures and the same aperture standard deviation.

3.6.3 Groundwater degassing

Mechanisms and observed gas contents in the field

There are at least two factors that may contribute to a considerable hydraulic conductivity reduction due to degassing. First, the occurrence of bubble trapping implies that gas may accumulate in the fracture, such that that the local degree of fracture gas saturation (i.e., gas volume per total fracture volume) is considerably greater than the evolving volumetric gas content $\Delta\theta_g$. Second, the non-linear relative hydraulic conductivity functions for unsaturated flow imply that hydraulic conductivity decreases considerably with increasing degree of gas saturation. However, none of these two factors can possibly contribute to hydraulic conductivity reduction unless a separate gas phase forms within the fracture pore space.

The above-mentioned evolution of a separate gas phase within the fracture is expected to increase water pressure gradients in the vicinity of the borehole relative to the single-phase case. This expected change in local water pressures under degassing conditions is illustrated schematically in Figure 3-31 for linear flow conditions. The thick line in Figure 3-31 illustrates the expected single-phase pressure distribution under water saturated conditions between the fracture outlet (x=0), where the water pressure equals the

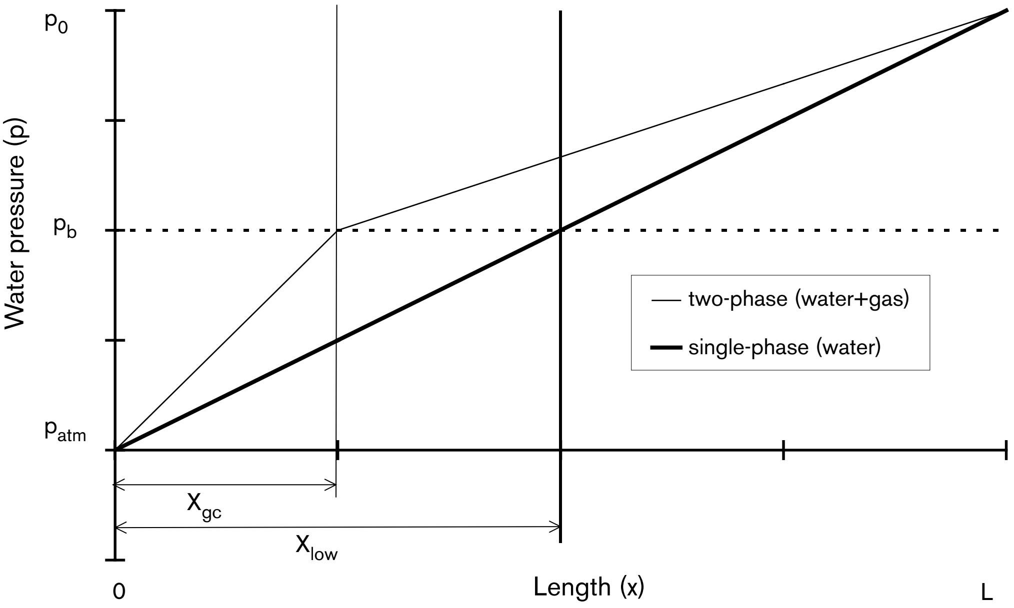


Figure 3-31. *Illustration of the expected effect of a local gas-containing zone X_{gc} on the pressure distribution for linear flow conditions: a comparison between single-phase and two-phase conditions.*

atmospheric pressure p_{atm}, and the outer boundary (x=L), where the water pressure equals p_0. The bubble pressure p_b is illustrated by the dashed line, and the low-pressure zone extent at saturated conditions X_{low} extends from x=0 to the intersection between the bubble pressure line and the single-phase water pressure line. The thin pressure line in Figure 3-31 illustrates the water pressure distribution that is expected as a result of a gas phase development within the low-pressure zone, and a local decrease in fracture transmissivity due to unsaturated water flow within this zone. Local transmissivity reduction implies steeper pressure gradient in the vicinity of the fracture outlet, causing the gas-containing zone under two-phase conditions X_{gc} to be smaller than the low-pressure zone under water saturated conditions (X_{low}; see Figure 3-31). Since the overall decrease in fracture transmissivity is depending on the extent of the zone where the transmissivities are decreased in relation to the full fracture extent (L in Figure 3-31, it is expected that the probability for degassing-related flow reductions increases as the ratios X_{low}/L and X_{gc}/L increase. Otherwise, if the developed gas phase occupies only a very small part of the water-bearing fracture, the effective hydraulic conductivity of the entire fracture will remain essentially unchanged.

A general restriction for the local occurrence of groundwater degassing is that the bubble pressure of the gas dissolved in the water needs to be higher than the local water pressure; otherwise the gas will not come out of solution, which prevents the evolution of a separate gas phase within the fracture pore space. Water pressures are often decreased down to atmospheric pressure when water is withdrawn from deep boreholes and drifts in the bedrock, for example, during hydraulic and tracer testing. Field data from different sites in the deep bedrock in Sweden suggest that the bubble pressures indeed can be higher than the atmospheric pressure, since up to 5 volumetric percent gas have been observed to evolve when lowering borehole pressures from formation pressure down to atmospheric pressure. At Äspö HRL, between 0.1% and 5% gas has been observed evolving at 350–400 metres depth. At Laxemar, the gas contents ranged between 2% and 5% and 1000 metres depth, and at the Stripa mine, the gas content ranged between 2% and 4% at 385 metres depth. At all the above-referenced sites, nitrogen is the dominating gas, occupying approximately 80% of the total gas volume. At the Wellenberg site in Switzerland, a change in gas composition and content with depth has been observed, with the more shallow groundwater being dominated by nitrogen and the deeper groundwater being dominated by methane. At 300–400 metres depth, the formation water is generally close to fully saturated with methane at formation pressure (with local existences of a free gas phase), implying even higher volumetric gas contents at atmospheric pressure conditions than for corresponding depths at the Swedish sites.

Hence, the gas content data suggest that the natural conditions are such that degassing is plausible in Swedish bedrock. Furthermore, degassing was hypothesised to have caused an observed inflow reduction during a hydraulic and tracer test series in the Stripa mine in Sweden. Then, the inflow to the drift was a factor eight smaller than the inflow measured at the same location in six boreholes forming a ring before the drift was excavated. As opposed to the drift case, water pressures around the boreholes were considerably above atmospheric pressure due to borehole pressure regulation, thus preventing degassing to occur around the boreholes. The potential occurrence and impact of degassing, relative to other phenomena that may have contributed to the observed inflow reduction in Stripa (such as changes in the rock stress conditions), could not be quantified based on available data. Without providing any conclusive answers, the Stripa observations thus raised important questions about whether or not and to what extent groundwater degassing may be expected to affect hydraulic property values that are determined from drift inflow measurements at large depths below the groundwater table, or from hydraulic tests in boreholes.

Borehole tests in the field

To address the potential degassing problem, the focus of an experimental field programme was directed towards borehole tests, because they are easier to control and may be conducted at much lower costs than drift experiments. The main objective was to investigate whether the lowering of pressures down to atmospheric pressures in a borehole intersecting a water bearing fracture would lead to degassing, unsaturated zone formation and, as a consequence, changes in the fracture hydraulic properties. During the pilot hole degassing test, there were no indications of considerable flow reductions due to degassing /Geller and Jarsjö, 1995/. The same result was obtained for two additional single-well tests /Jarsjö and Destouni, 1997/. The gas contents during all these three tests were relatively low; 2.4% and less. Therefore, a dipole test was conducted /Jarsjö and Destouni, 1997/ where the gas content in the test hole was raised to 13% through continuous injection of gas (N_2) saturated water in a nearby borehole. The results for the dipole test showed that the inflow was considerably reduced under these conditions; the flow rates at the end of the test were approximately 50% of the ones that were expected for single-phase conditions. The field tests hence indicate that considerable degassing effects may occur in boreholes only under certain conditions.

Laboratory experiments

Through a series of laboratory experiments, degassing effects were further observed under a wide range of different conditions (e.g., different fracture aperture distribution, gas content, flow geometry and boundary pressure), showing that the magnitude of flow reductions due to degassing indeed differed considerably between the considered set-ups. For instance, radial and linear flow experiments in transparent epoxy replicas of natural rock fractures (sampled at the Äspö HRL and in the Stripa mine) showed that evolved gas contents between 3% and 15% can cause fracture gas saturations of up to 40 volumetric percent, and considerable reductions in flowrates as compared with corresponding single-phase conditions. For linear flow experiments /Gale, 1999/ in actual rock fractures that were re-assembled in the laboratory, considerable fracture transmissivity reductions were observed at lower evolved gas contents than for the radial flow experiments. Visualisation experiments in transparent, artificial fractures, indicated that there are instances where gas bubbles do not accumulate in the fracture (as in the above-mentioned experiments) but are swept away by the (converging) flow. As a result, the relative flowrate reductions were not so great, even though gas bubbles formed within the fracture pore space.

Model parameters

In order to interpret and predict the occurrence of groundwater degassing, there is a need to identify governing parameters and conditions. Provided that the different behaviours observed in the laboratory and in the field (i.e., occurrence or absence of flow reductions) can be explained by occurrence or absence of groundwater degassing, then some degassing-related condition must have been favourable in the cases where flowrate reductions were observed, and not so favourable in the other experiments. Basic degassing relations show that the extent of the low-pressure zone, X_{low}, in relation to the total fracture length dimension, L, should provide some indication on whether or not it is reasonable to expect degassing-related flow reductions (see Figure 3-31). It was therefore investigated whether or not there is a correlation between the relative extent of the low-pressure zone, X_{low}/L, and the actual outcome of degassing experiments and observations in the field and in the laboratory (in terms of the occurrence or absence of an observable flow reduction). More specifically all available experiments were considered that were conducted either in natural rock fractures, or in replicas of natural rock fractures.

The results of this comparison showed that in all experiments where degassing either certainly did cause the flow reduction, or was a likely cause for it, the value of X_{low}/L was greater than for the tests where degassing did not cause any significant inflow reductions. Considering that in total eight (sets of) experiments where accounted for in this analysis, the probability for this X_{low}/L-outcome to occur randomly, i.e., to occur even if there were no correlation between X_{low}/L and observed flow reductions, is only 1.8%. This clearly supports that the observed flow reductions are degassing-related.

Development of predictive degassing models

Fracture aperture based degassing expressions for gas saturation degree and relative transmissivity were developed for the condition that gas will accumulate in the fracture, i.e., that the bubble trapping probabilities are high. This condition can be checked using the relation of Jarsjö and Destouni /1998/, which expresses the probability of capillary bubble trapping in variable aperture fractures. Since low bubble trapping probabilities imply lower gas saturations and lower flow reductions, the developed expressions for gas saturation degree and relative transmissivity constitute limiting cases. Note, however, that experimental results indicated high bubble trapping probabilities in natural fractures, implying that these limiting cases often apply for the observed natural conditions.

The degassing relations for gas saturation degree and relative transmissivity were developed through combining a constraint for the existence of a free gas phase with the implications of capillary effects in the fracture pore space. More specifically, this was done by relating the gas content dissolved in the water phase (or corresponding bubble pressure) to a critical aperture, below which gas is no longer assumed to exist as a separate phase. The physical motivation for this assumption is that the phase pressure would be too high (i.e., higher than the bubble pressure) for the gas to exist under equilibrium conditions in apertures smaller than this critical aperture, due to capillary effects. The assumption that there is such a critical aperture was confirmed by experimental observations under degassing conditions in transparent epoxy replicas of rock fractures, where water was observed to fully occupy the tighter aperture regions. The same experiments furthermore showed that water and gas co-existed in the wider aperture regions (with apertures greater than the critical aperture). This condition was considered in the model relations, through the parameter α, which quantifies the fraction of water in the wide aperture region; hence ($1-\alpha$) quantifies the fraction filled with gas in this region. A comparison between model predictions and experimental observations for both gas saturation degree and transmissivity reduction showed that a value of α of 0.2 yielded the best predictions. This value was therefore used in the modelling of the field results. However, for α-values between 0.2 and 0.4 the model results were relatively insensitive to the actual value of this parameter, indicating that the exact α-value is not a critical parameter within this range.

Comparing model predictions with the outcome of borehole tests

The derived expression for relative transmissivity was used to predict the outcome of the conducted field borehole tests. In three of these borehole tests (the single-well tests), the transmissivity reduction was negligible, whereas a considerable, (50%) reduction was observed in the dipole test. This experimental result was reproduced using the developed degassing-based expression for relative transmissivity. However, some of the parameters used in this expression were based on more general, non site-specific estimates, such as the radius of influence (R)-value and the aperture standard deviation ($\sigma_{\ln a}$)-value. With the aim to investigate whether or not the previously discussed model results were sensitive to the assumed values of these parameters, and whether or not more general conclusions can be drawn regarding degassing effects in the vicinity of boreholes, it the impact of different plausible parameter values on the modelled relative transmissivity was investigated.

In this investigation a range of parameter values were considered that are relevant for rock fractures intersecting boreholes at depths between 20 and 600 metres. The investigation showed that the model results were robust, i.e., insensitive to the ratio between well radius and radius of influence (r_w/R), the mean aperture $\mu_{\ln a}$, the aperture standard deviation $s_{\ln a}$ and the boundary pressure p_{bound} values within the considered ranges. This robustness further implies that the model predictions of field borehole tests are also robust for these realistic parameter ranges.

We furthermore identified a single, dominant parameter for degassing effects in boreholes, namely the ratio between the bubble pressure and the boundary pressure (p_b/p_{bound}). Considering radial borehole inflow, we showed that this parameter considerably influences the modelled relative transmissivity, particularly for relatively large ratios (more than about 0.8). For values below 0.8, the modelled relative transmissivity T_{rel} was close to unity, implying that flow reductions due to groundwater degassing are negligible. Under natural conditions at the Äspö HRL, the gas contents (mainly nitrogen) at atmospheric pressure are relatively low, around 3% (sometimes even considerably lower). This corresponds to a nitrogen bubble pressure of about 260 kPa. At 200 metres depth, the borehole pressure at no flow (or boundary pressure p_{bound}) is approximately equal to the hydrostatic water pressure of 2000 kPa. The above-mentioned p_b/p_{bound} ratio is thus around 0.13, which is far below the value of 0.8. Hence, based on both the borehole test observations and the consistent model predictions, it was concluded that groundwater degassing will not cause considerable inflow reductions in fractures intersecting open boreholes under conditions normal for Swedish granitic bedrock.

Comparison with the Stripa SDE experiment

The relatively large inflow reductions observed during the Stripa simulated drift experiment (SDE) were possibly a result of groundwater degassing, although there were also other possible causes for the observed flow reductions. The hydrostatic water pressure was 2300 kPa and the gas content in the water was about 3%, implying a bubble pressure p_b of 260 kPa and a relatively low p_b/p_{bound} ratio of 0.11. Both experimental and model results show that degassing would not cause considerable transmissivity or flow reductions around boreholes for such a low ratio. Considering the difference in size between a borehole and a drift, we investigated the possible influence of scale effects for ambient conditions relevant in the SDE. The considered effects included spatial variability in the fracture aperture statistics (i.e., considering that the larger drift may be intersected by a larger number of hydraulically different fractures), and slow gas re-dissolution (i.e., considering that the ratio between the gas-water interfacial area and the gas volume may decrease as the scale and the total gas volume increase). The predicted relative transmissivities were found to be relatively insensitive to spatial variability in the fracture aperture statistics. In contrast, the relative transmissivity predictions were considerably different under the assumption that the gas will not re-dissolve once it has formed in the fracture pore space (even though local pressures increase above the gas bubble pressure as a consequence of the local transmissivity reduction due to the gas formation). Under this assumption, a considerable transmissivity reduction was predicted for the SDE, which is consistent with the experimental observations.

Implications

We conclude that the Stripa SDE cannot be reproduced by the degassing model unless relatively slow gas re-dissolution is assumed; we considered the limiting case that the gas could not re-dissolve at all once it had formed. This implies non-equilibrium conditions between the separate, evolved, gas phase and the gas dissolved in the water phase. The modelling of numerous laboratory experiments and boreholes tests, however, clearly showed that at these experimental scales, it is appropriate to assume that equilibrium conditions will be reached after some time. Whereas slow gas re-dissolution provides the only possible degassing-based explanation for the reduced inflows observed during the Stripa SDE, there are also alternative explanations for these reductions, such as stress-induced fracture deformation. With regard to the observed inflow reduction in the dipole degassing (borehole) test, however, neither fracture deformation nor turbulence constitute likely explanations for the observations. Further, the large number of experimental observations of groundwater degassing at the laboratory scale and the boreholes field scale, in conjunction with consistent model predictions, imply that the degassing processes at these relatively small experimental scales are well understood and that the corresponding conclusions are empirically well founded.

3.7 Hydrochemistry modelling/Hydrochemical stability

3.7.1 Background

The chemical properties of the groundwater affect the canister and buffer stability and the dissolution and transport of radionuclides. It is therefore important to know the possible changes and evolution of the groundwater chemistry during the repository life time. The processes which influence and control pH, redox properties and the salinity (occurrence, character and stability of both saline and non-saline groundwaters) must be understood. In addition it is also necessary to know the possible variation in concentration of those elements which affect the canister corrosion, buffer stability and solubility and migration of radionuclides.

In the past five years this project has been carried out within the framework of the Äspö agreement between SKB and Posiva. It also covers the technical parts of the participation in the EC EQUIP project and the modelling Task #5 within the framework of the Äspö Task Force for modelling of groundwater flow and transport of solutes. The project is ended and the final report is under way.

3.7.2 Objectives

The objectives of this project are:

- To clarify the general hydrochemical stability (= groundwater chemistry of importance for canister and bentonite durability and radionuclide solubility and migration).
- To describe the possible scenarios for hydrochemical evolution at Äspö over the next 100 000 years, separated into time slabs of 0–100, 100–1000, 1000–10 000 and 10 000–100 000 years.
- To develop a methodology to describe the evolution at candidate repository sites, e.g. Olkiluoto.

3.7.3 Model concepts

Geochemical interpretation of groundwater-rock interaction along flow paths makes use of the results from groundwater chemical investigations, i.e. chemical constituents, isotopes and master variables pH and Eh in combination with the existing mineralogy, petrology and termodynamic data. Useful tools for these calculations are reaction path codes like NETPATH and equilibrium-mass balance codes like EQ 3/6. These codes are frequently used in hydrochemical studies.

A newly developed concept and code, M3, start from the assumption that it is mixing and not chemical reactions that is the dominating process affecting the chemical composition of the groundwater within the investigated system. The principal assumptions behind this concept is that the varying hydraulic conditions of the past have created the complex mixing pattern presently observed. When the effects of mixing have been evaluated, mass balance calculations (resulting from chemical reactions) are then made to explain the difference between the ideal mixing and the observations. A good description of the different modelling approaches is found in the Applied Geochemistry Journal, vol 14, No 7, Sept. 1999.

The modelling strategy for the Hydrochemical Stability project involve:

- Identification of the dominant (chemical) processes for Finnish and Swedish sites.
- Geochemical mixing for Äspö and Olkiluoto.
- Site intercomparison and comparison between the M3 and NETPATH techniques based on data from Olkiluoto.
- Transient hydrodynamic modelling for Äspö and Olkiluoto.

The intention with the strategy is to be able to compare the results of the traditional hydrochemical modelling with the results from M3 and to compare the outcome of the hydrodynamic modelling with the results from M3. The latter comparison is done within the Task #5 of the Äspö Task Force for modelling of groundwater flow and transport of solutes.

The EQUIP project has the specific objective to trace the past hydrochemical conditions through investigation of (calcite) fracture filling minerals. The outcome will be compared to the results from the hydrogeological and hydrochemical models and thus provide an independent check of the long term stability of the groundwater flow and chemistry.

3.7.4 Results

Task#5

The time for the integrated modelling of Task#5 has been prolonged and the results of the individual modelling teams will be printed by the middle of this year. The evaluation of the entire Task#5 will start and an external review of the modelling task are planned to be printed by the end of 2001.

The conclusions so far is that there is a need to obtain information on both hydrological and hydrochemical properties from the same location at the same time. Even though there is a huge database on hydrochemistry, many modellers still would have needed more time series observations from more observation points.

In general there is an agreement that the hydrochemical information has helped constraining the groundwater flow models.

EQUIP

Calcite from open fractures mainly at Äspö and Laxemar, sampled at depth ranging from 25 to 1600 metres, have been analysed within the Swedish part of the EQUIP programme. The results were presented in the HRL annual report of 1999 /SKB, 2000a/ and are only shortly presented below:

The studies reveal that several generations of calcite can be identified, chemical zoning is common, and the influence on calcite precipitation of fresh or marine water decreases with depth.

A compilation of the existing data results in identification of 6 different calcite generations:

1. Calcite precipitated from meteoric water at low temperature conditions most common in the upper 50 to 100 metres of the bedrock but may exist down to 1000 m.
2. Calcite precipitated from brackish water (Baltic sea water?) at low temperatures is found down to a depth of approximately 500 m and is possibly (or partly) of postglacial age.
3. Calcite precipitated from oceanic water is found down to a depth of 300 metres. This calcite may as youngest be Eemian in age (117 000 to 130 000 years) but may well be considerable older.
4. Calcite precipitated from glacial/cold climate water.
5. Calcite precipitated from brine water at temperatures between 60 and 150°C.
6. Calcite precipitated from hydrothermal solutions usually associated with epidote, quartz, adularia and fluorite.

The occurrence of calcite types 1 to 4 decrease with increasing depth, whereas calcite of type 6, and to some extent calcite of type 5 increase with depth. Calcite generations of type 5 and 6 constitute the thickest precipitations (mm thickness) whereas the low temperature calcite constitutes extremely thin coatings or rims (µm thickness) on older hydrothermal calcite precipitates. Reliable age determinations of the low temperature precipitates are therefor very difficult to obtain.

It is remarkable that calcites precipitated from brackish and marine water are only found down to ca 500 m depth whereas calcites with meteoric/cold climate recharge signatures can be traced to larger depth, possibly as deep as 1000 m. One explanation for this may be differences in hydraulic head: Durig periods when Äspö/Laxemar was covered by sea (brackish or oceanic) the hydraulic driving force would not allow deep penetration of the marine water.

3.7.5 Conclusions and implications to repository perforemance

The first period of 100 to 1000 years are most important for the performance of a deep repository. During this period, the amount of radionuclides is several powers of ten higher than during later periods. The hydrochemical stability of a repository site is therefore most important for the first 1000 years.

Expected hydrochemical conditions during the first 1000 years: Stable groundwater flow conditions, giving steady state mixing and reaction processes. Chemical factors that influence this situation:

- Fast precipitation/dissolution reactions (equilibriuum) for several fracture filling minerals: calcite, iron oxyhydroxides and sulfides, giypsum, fluorite, etc. These reactions control the chemistry of HCO_3^-, Ca^{2+}, Fe^{II} and Fe^{III}, SO_4^{2-}, F^-.
- Ion exchange reactions: Na^+, Ca^{2+} and Mg^{2+} ratios.
- Fast weathering reactions: control of silica and aluminium groundwater concentrations.
- (biological) redox reactions: control of organic material, Fe^{III}/Fe^{II} ratio, S^{VI}/S^{II}, O_2, CH_4 and H_2, etc.

Expected range of concentrations for groundwater constituents will be defined based on the present day situations.

What could change this picture during a 1000 or 10 000 year period? Man-made climate changes could change local precipitation regimes, and thus affect slightly groundwater flow conditions. Slow global cooling will change the hydrological regime in the long run. Fennoscandinavian land upheaval will also affect the groundwater paths.

During 10 000 to 100 000, the hydrochemical conditions will be influence by the local climatic conditions which will probably have large variations during this period. The process that affects hydrochemical stability is varying groundwater flow conditions. These variations will introduce changes in mixing groundwater patterns. Possible scenarios, and main effects are:

Scenario	**Effects**
1. Colder climate, which eventually will lead to permafrost	Changes in precipitation amounts and recharge. Permafrost will probably change groundwater flow paths.
2. Ice sheet: glaciation and deglaciation.	Infiltration of glacial melt water. A minimum amount of cations is quickly achieved by fast water-mineral interactions, as described above. Perhaps high O_2 contents. Oxidising conditions might reach repository level depending on the ratio between groundwater flow and chemical and microbial reactions.
3. Marine conditions: either freshwater or saline water regimes (lake/sea coverage).	Under saline marine conditions, differences in water densities might cause a "turnover": relatively fast groundwater flows in vertical fracture zones.
4. Interglacial periods (land)	Climate conditions similar to present, or perhaps colder. Hydrochemistry probably similar to the first 10 000 year period.

3.8 Matrix Fluid Chemistry

3.8.1 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. Migration of matrix fluids will be facilitated by small-scale fractures and fissures. 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.

3.8.2 Objectives

The main objectives of the experiment are:

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

3.8.3 Experimental Configuration

The experiment has been designed to sample matrix fluids from predetermined, isolated borehole sections. The borehole was selected and drilled on the basis of: a) rock type, b) mineral and geochemical homogeneity, c) major rock foliation, d) depth, e) presence and absence of fractures, and f) existing groundwater data from other completed and on-going experiments at Äspö. Special equipment 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 uranine content, f) the collection of fluids (and gases) under pressure, and g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

3.8.4 Programme

During the latter part of 1999 a Feasibility Study was carried out on solid drillcore material representing one of the borehole sections isolated for sampling matrix fluid. The first stage of the study comprised the basic mineralogy and major and trace element geochemistry to generally characterise the rockmass. These data were then used to initially characterise fluid inclusion populations and to identify which elements and isotopes to be determined. Crush/leach experiments were conducted also to indicate the nature of the matrix fluid. During 2000 a full programme of study has been on-going and activities carried out have involved: a) mineralogical studies, b) porosity measurements, c) crush/leaching experiments, d) Äspö diorite permeability test, e) fluid inclusion studies, f) matrix water 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 Experiment borehole. The first half status of the project is reported in Smellie /2000/.

3.8.5 Drillcore studies

One of the major problem is to separate and analyse the pore or matrix fluids in the interconnected pore system of the rock matrix. Pore fluids are important to characterise since accessibility of these fluids not only influences the chemistry of the formation groundwaters, but the fluid chemistry can also to be influenced by the formation groundwaters by out- and in-diffusion processes respectively. The inaccessible fluids in closed-off pore spaces, at microfracture/fissure dead-ends, and contained in fluid inclusions are of very little importance unless tectonic stresses induce connected porosity and cause fracturing of the fluid inclusions. These effects may also be caused by water-rock interaction (i.e. dissolution) over long time periods. In both cases pore fluids and fluid inclusion fluids become accessible via the interconnected porosity and may be further transported through the rock by diffusion and, in some cases, ultimately by advective flow via micro fissures/fractures. If these fluids are highly saline, they can contribute to increasing salinity of the formation groundwaters.

The matrix drillcore studies to date indicate that the interconnected physical or total rock porosity is similar throughout the drillcore length studied even though two rock types (Äspö diorite and Ävrö granite) have been identified. Crush/leach experiments have indicated that the total fluid content in the rock (e.g. from fluid inclusions, pore fluid, interstitial fluid etc) is highly saline and most of this can be explained by the influence of the fluid inclusions. However, the specific chemistry of the accessible pore or matrix fluid is still not known. The permeability experiment has tried to address this by attempting to force out the connected pore fluids by pressurising deionised water through the core. This has still not yielded any results after almost 2 years.

3.8.6 Sampling

Since the sampling carried out in borehole Section 4 (4.66–5.26 m) in December 1999, borehole Section 2 (green colour; 8.85–9.55 m) has continued to show a small, but steady pressure increase during 2000 (Figure 3-32). This will be allowed to continue until adequate matrix fluid has accumulated (total section volume of 245 mL). This is scheduled for late 2001 and the sampling and analytical protocol will involve a more sophisticated approach that will include gas analysis. A renewed pressure increase in Section 4 (blue colour) indicates that the section is being refilled and resampling is scheduled also for 2001. The much slower accumulation of fluid in Section 2, plus the absence of large fluid volumes in the adjacent Section 1 (red colour; already opened in 1999), may suggest a lower connected porosity and therefore more representative matrix fluid composition than collected from borehole Section 4.

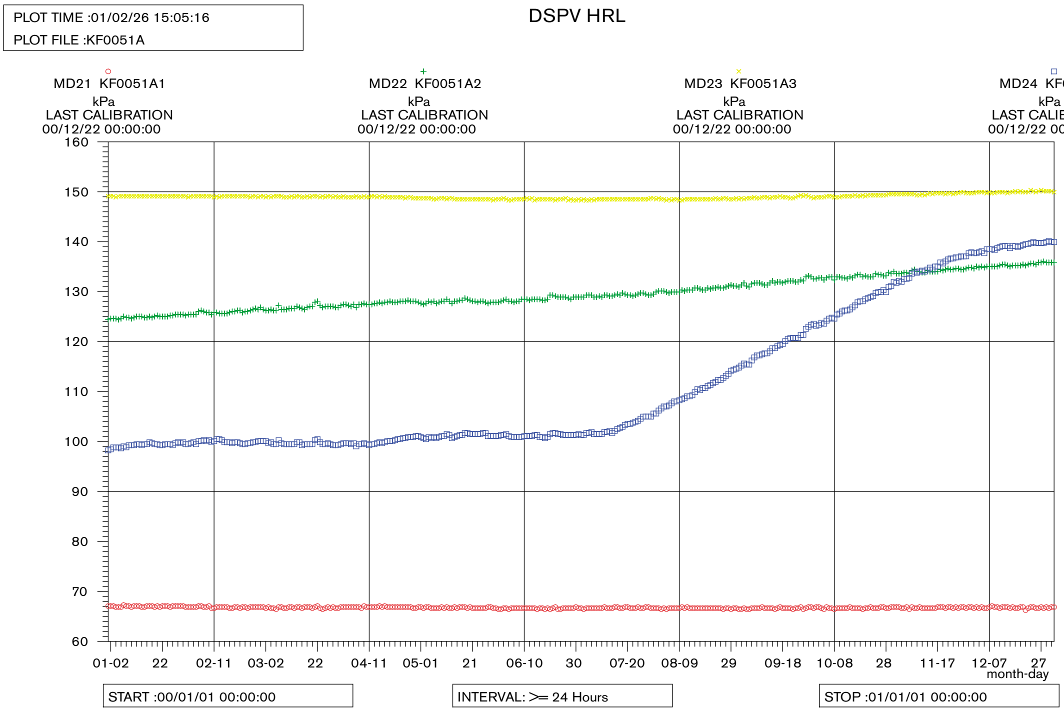


Figure 3-32. *Pressure monitoring curves for each of the four isolated borehole sections; 1(red), 2 (green), 3 (yellow) and 4 (blue). Sections 2 and 4 are demarcated for matrix fluid sampling.*

3.8.7 Hydraulic character of the rock matrix

General

Information used in estimating the hydraulic properties of the rock matrix included:

- changes in pressure recorded from each of the four isolated borehole sections of interest over a period of two years (Figure 3-32),
- after a period of 18 months borehole sections 1 and 4 were opened; Section 1 was dry but Section 4 gave 160 mL of water out of a total volume of 210 mL ,
- petrological data have located a fine fracture intersection with the borehole at 4.035 m were a packer is located; this intersection is some 56.5 cm from Section 4 towards the tunnel, and
- mineralogical data have suggested that the Äspö diorite may be more porous than the Ävrö granite, although this is presently not reflected in the measured connected porosity.

Predictions

Estimated times to accumulate 250 mL matrix fluid (approximating to the respective volumes of Sections 2 and 4 earmarked for sampling) were predicted based on a range of hydraulic conductivity values. Both radial and spherical Darcian flow were considered assuming differential pressures within 10–35 bar and a radius of influence 5–10 m. The results of the predictions are shown in Figure 3-33. The increase in pressure in borehole Section 4 after the first 15 months (June 1998 to December 1999) suggests that the hydraulic conductivity in the matrix rock block lies somewhere around 10^{-14}–10^{-13} ms^{-1}.

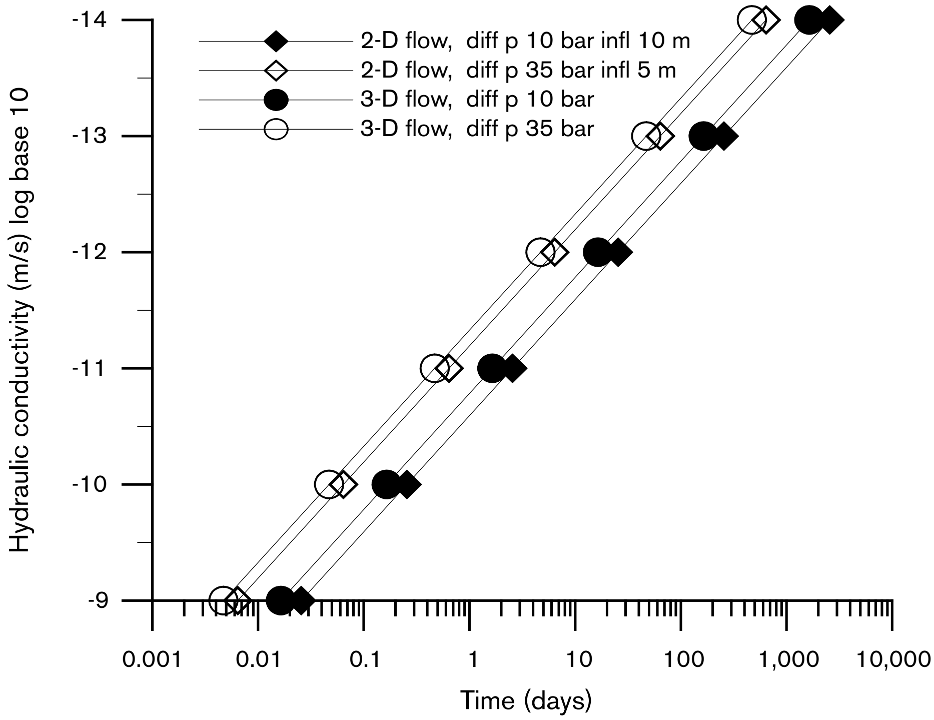


Figure 3-33. *Predicted times to accumulate 250 mL of matrix fluid, based on a range of hydraulic conductivities, considering both radial and spherical Darcian flow and assumed differential pressure within 10–35 bar and radius of influence 5–10 m.*

Following the opening of the two borehole sections in December 1999, when 160 mL of water was recovered from Section 4, out of a maximum of about 180 mL (around 20 mL residual volume was inaccessible due to packer/borehole geometry), further calculations were made. From the measured inflow rate, the actual pressure in the borehole section, and an estimate of pressure in the surrounding rock creating differential pressures within 10–35 bar and radius of influence 5–10 m, the hydraulic conductivity of the matrix rock block was calculated. Even though there are uncertainties in estimated pressure and the assumed flow regime, both radial and spherical Darcian flow, the calculated hydraulic conductivity of $1 \cdot 10^{-14}$–$6 \cdot 10^{-14}$ ms^{-1} of the matrix rock block is judged reasonable and in accordance with the earlier predictions.

Fluid movement

The chemical analysis of the sampled fluid from borehole Section 4 (see discussion in Section 8.3) showed a water composition more typical of conductive minor water-bearing fractures in the near-vicinity of the matrix borehole (e.g. transmissivites of 10^{-10}–10^{-5} m^2s^{-1}) than what was expected from the matrix fluid. Hence, the existence of preferential "flow paths" in the matrix rock, closely located to minor water-bearing fractures seems possible. In this respect the very fine, semi-permeable fracture/fissure (located on the BIPS image) intersecting the borehole some 56.5 cm from Section 4, may play an important role; microscopic characterisation of this fracture is forthcoming.

Based on present knowledge of the local bedrock hosting the matrix borehole (~ $10m^3$), and the groundwater hydraulics and chemistry of the near-vicinity bedrock environment (~ $50m^3$), a preliminary conceptual model summarising the hydraulic nature of the matrix rock environment, is presented in Figure 3-34. The solid arrows in the figure

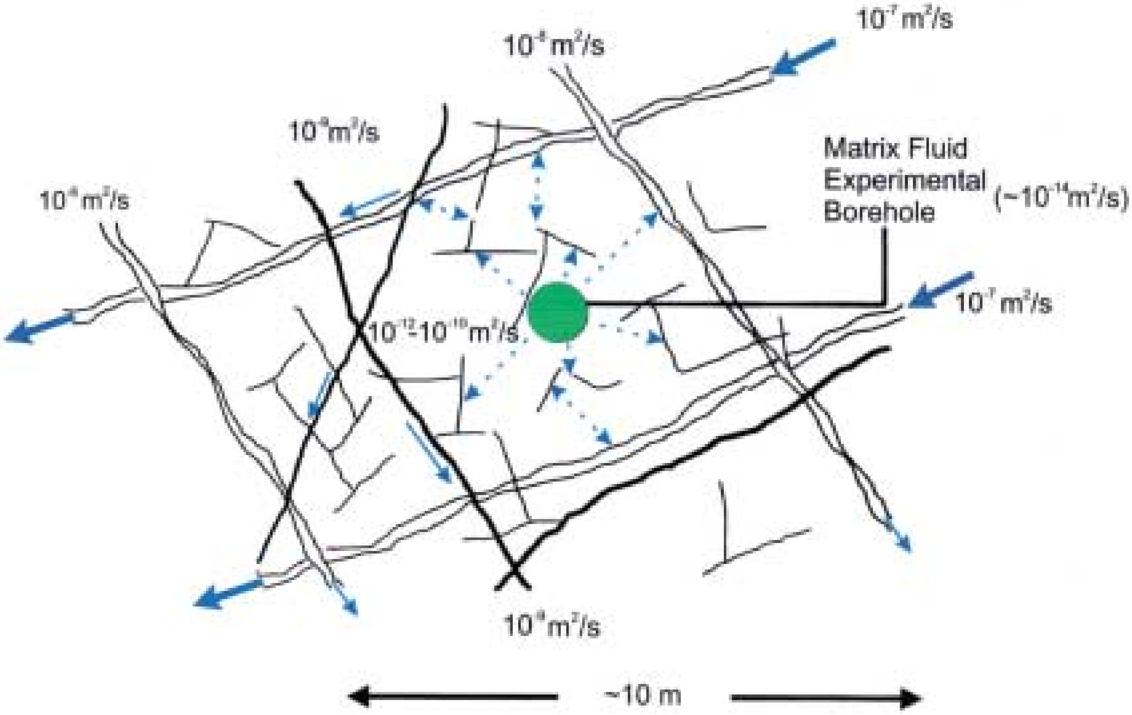


Figure 3-34. *Schematic conceptualism of the hydraulic character of the bedrock environment adjacent to the matrix borehole. (Solid arrows represent advective groundwater flow; broken arrows represent mainly in- and out-diffusion processes.)*

indicate advective groundwater flow and the broken arrows represent mainly in- and out-diffusion processes through the rock matrix.

3.8.8 The surrounding hydrochemical environment of the matrix borehole

General

Matrix fluids are here considered to constitute the pore fluids in the rock matrix. However, the accessibility of these fluids, and their ability to move through the rock matrix, will depend on whether or not the pore spaces are interconnected. Assuming interconnected pore spaces, it is important to try and relate the matrix fluid chemistry to the chemistry of groundwaters present in nearby minor fracture zone(s) of low hydraulic transmissivity ($T = 10^{-12}$–10^{-9} m^{2}s^{-1}), since it will be these groundwaters that will come in contact eventually with the engineered barrier materials following repository closure.

Since these fracture zones represent variations in transmissivity, orientation and also represent different geographical locations, they may also be characterised by different hydrochemical signatures. These signatures may be the result of one or any combination of the following processes occurring within and close to the fracture zones:

- water/rock interaction during long residence times,
- mixing of palaeowaters from past marine stages,
- mixing of palaeowaters from past glacial periods,

- mixing of modern groundwater components, and
- evolution of groundwater chemistry by out-diffusion of pore fluids from the rock matrix into fracture zones, or *vice versa*, in-diffusion of fracture waters to the matrix.

These are important points to be addressed, and to deal with them adequately a reliable hydraulic and hydrochemical database is required. To compile a database of fracture groundwater chemistry, related to hydraulic conductivity and at equivalent depths to the matrix fluid experiment, three sets of suitable data have been used:

- data from fractures present in the near-vicinity of the matrix fluid chemistry experiment borehole, i.e. from the "J" niche as part of the on-going CHEMLAB and Microbe experiments,
- data from the TRUE Block Scale Experiment programme, and
- data from the deposition holes (and their surroundings) resulting from the Prototype Repository.

Hydraulic parameters

The hydraulic data from the TRUE Block Scale experiment is well documented and measured hydraulic transmissivities of the sampled fractures range from 10^{-8}–10^{-5} m^2s^{-1}.

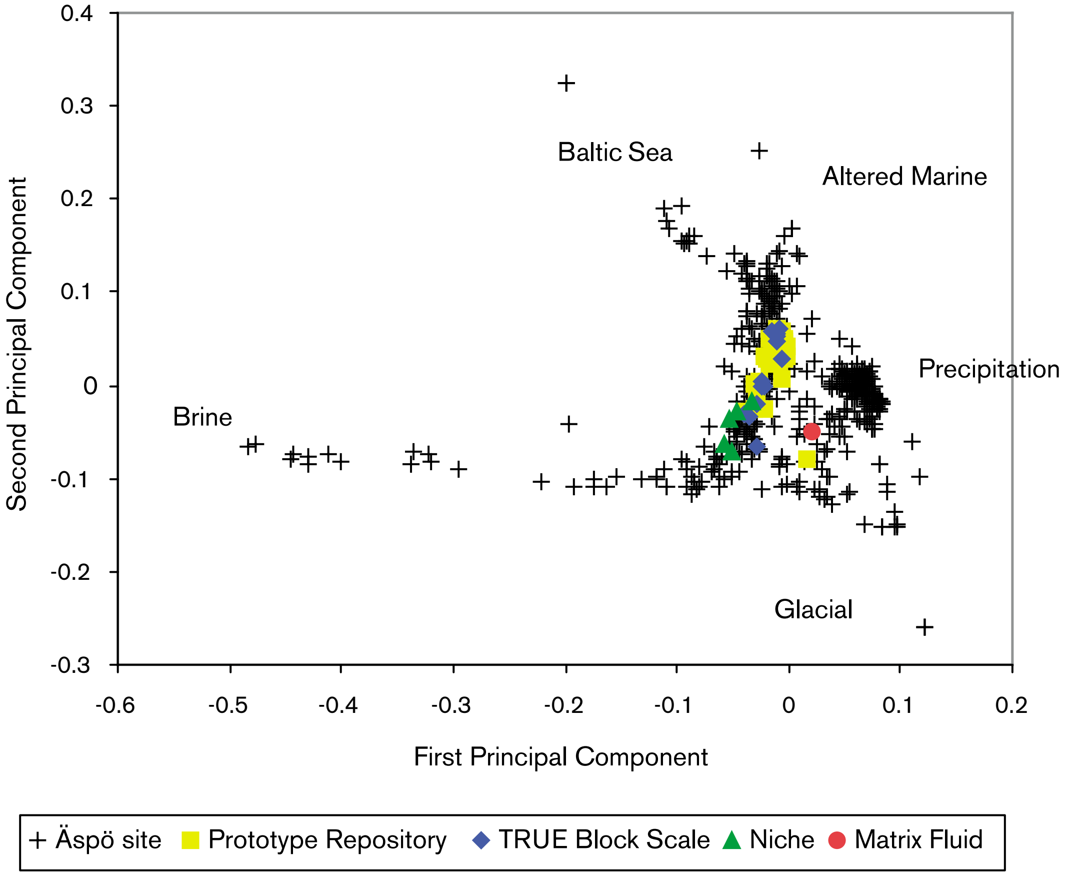
Hydraulic data from the Prototype Repository was obtained in close collaboration; several borehole sections were selected for quantitative hydrochemical characterisation with transmissivities ranging from 10^{-10}–10^{-8} m^2s^{-1}. No quantitative hydraulic data are available from the "J" niche but measured groundwater flow rates (0.6–4.0 mL/min) from packed-off intervals in boreholes KJ0044FO1, KJ0050F01, KJ0052F01, KJ0052F02, KJ0052F03 (Microbe Experiment) would suggest transmissivities in the range of 10^{-8}–10^{-7} m^2s^{-1}.

Hydrochemistry

The general chemical character of the groundwaters from each of the sampled sites can be seen from the PCA plot in Figure 3-35. The exact location of the "matrix" sample is uncertain as all the chemical and isotopic parameters are not known due to the small volume of water obtained. Tabell 3-3 shows the average values for TRUE Block Scale, Prototype Repository and J-tunnel (Chemlab/Microbe) experiments, compared to the Matrix data and Prototype Repository sample KA3572G01.

Figure 3-35 shows a clear separation of the "J" niche and Prototype Repository samples with the TRUE Block Scale samples extending over the full range of both groupings; the "Matrix" sample and that of KA3572G01 (Prototype Repository) are clearly different. The distribution of the plotted data is controlled by variation of the saline, glacial and Baltic Sea components; the greater the Baltic component, the less the glacial (and saline) component.

To date the general conclusion is that over the range of hydraulic conductivity represented by the sampled fractures, most show little obvious correlation with groundwater chemistry. The data indicate an influx of a modern groundwater component, such as Baltic Sea and meteoric precipitation waters, associated with the hydraulic drawdown caused by tunnel construction, to the detriment of older saline and glacial melt water components which have been diluted or removed. This has been particularly apparent with the Prototype Repository samples, despite the generally low transmissive character



First Principal Componet = – 0.49[Na] – 0.03[K] – 0.01[Ca] – 0.03[Mg] + 0.13[HCO_3] + 0.24[Cl] + 0.16[SO_4] – 0.17[^2H] + 0.75[^{18}O] + 0.25[^3H]
Second Principal Component = – 0.25[Na] + 0.35[K] + 0.04[Ca] + 0.45[Mg] + 0.31[HCO_3] – 0.69[Cl] – 0.18[SO_4] – 0.09[^2H] + 0.06[^{18}O] – 0.003[^3H]
Variance: Comp. 1 = 40%; Comp. 1+2 = 70%
Matrix Fluid sample, chemical composition:
Na = 2200; K = 11.4; Ca = 964; Mg = 7.76; HCO_3 = 185 (mean value); Cl = 5180; SO_4 = 26; ^2H = –87.9; ^{18}O = –11.6; ^3H = 0 (assumed to be; no measurement)

Figure 3-35. *PCA plot showing distribution of groundwaters from the TRUE Block Scale, Prototype Repository and "J" niche experimental sites. These data are related to the overall Äspö database and to the approximate position of the "Matrix Fluid" sample.*

of the sampling locations, probably due to their near-vicinity to the excavated tunnel opening. Nevertheless there are indications that at least one of the lower transmissive fractures (KA3572G01; 10^{-9} m^2s^{-1}) has been less influenced by the drawdown due to a longer response time, retaining a lower Mg content and more negative ^{18}O signature, together with an overall higher total dissolved solids (TDS) content. This may reflect a different fracture orientation than the other sampled fractures. Drawdown effects are less evident from the J-tunnel and TRUE Block Scale sites probably due to the sampling locations being further from the excavated tunnel opening.

The "matrix" sample, whilst reflecting a generally similar major ion character to nearby fracture compositions (with the exception of SO_4 and Mg), exhibits anomalous chlorine isotope and strontium isotope signatures and higher contents of most trace elements which may be more characteristic of a "true" matrix component. It is hoped that the sampling from borehole Section 2 scheduled for later this year will shed more light on the matrix fluid chemistry and its origin.

Tabell 3-3. Average values for TRUE Block Scale, Prototype Repository and J-tunnel (Chemlab/Microbe) experiments, compared to the Matrix data and Prototype sample KA3572G01.

Element	TRUE Block [n=8] (mg/L)	Prototype [n=7] (mg/L)	KA3572G01 [n=1] (mg/L)	"J" Niche [n=5] (mg/L)	Matrix [n=1] (mg/L)
Na	1 983	1 887	2 340	2 286	2 200
K	7.9	9.1	10.3	9.11	11.4
Mg	42.4	86.4	24.8	54.1	7.8
Ca	1 396	770	800	1 996	964
Fe	0.09	0.34	–	0.90	0.24
Si	5.7	7.9	5.4	5.7	7.6
F	1.2	1.3	1.2	–	–
Cl	5 675	4 210	4 810	6 944	5 160
Br	30.7	19.9	27.2	39.3	43.16
SO_4	363	308	617	447	26
Alkalinity	19	155	–	40	Approx.170–200
pH	8.0	7.3	7.4	7.4	6.7
	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
Li	860	360	435	920	274
Sc	<0.01	0.020	0.024	0.540	0.099
Mn	280	510	–	410	890
Rb	28	30	35	29	31
Sr	19 900	10 780	15 700	33 780	18 600
Y	0.145	0.130	0.118	0.331	0.198
Cs	2.37	2.29	1.43	3.63	0.685
Ba	60.3	52.3	59.3	69.4	425
La	0.13	0.05	0.15	0.17	1.29
Ce	0.29	0.14	0.07	0.19	0.86
Nd	0.03	0.02	0.02	0.06	0.38
Th	<0.005	<0.005	<0.005	<0.004	<0.4
U	0.006	0.030	0.018	0.030	0.103
^{3}H	4.4	8.4	4.7	2.9	–
$\delta\,^{18}O$	–9.6	–8.0	–10.1	–10.6	–11.6
δD	–75.9	–66.7	–80.9	–79.6	–87.9
^{14}C	60	70	–	–	–
$\delta\,^{37}Cl$	+0.03	–0.28 to +0.16	+0.27	+0.34	+0.61, +0.59
$\delta\,^{11}B$	47.23	45.97	51.87	–	–
^{34}S	25.3	25.6	–	–	–
$^{87}Sr/^{86}Sr$	–	0.717563	0.714990	–	0.714561

^{3}H (TU); δ ^{18}O (‰ SMOW); δD (‰ SMOW); ^{14}C (pmc); δ ^{37}Cl (‰ SMOC); δ ^{11}B (‰ CDT); ^{34}S (‰ CDT).

3.8.9 Future activities and milestones

The following activities planned for the immediate future will include:

- continuation of drillcore crush/leach experiments with specific emphasis on lithological variation and porosity profiles,
- continuation of the permeability test,
- continuation of fluid inclusion mineralogical/petrographical charaterisation and chemistry,
- expand coverage of drillcore porosity measurements (some integrated with the crush/leach experiments) to achieve a better idea of large-scale heterogeneity or homogeneity in the matrix block, and also to further characterise the Ävrö granite rock type,
- detailed study of 1–2 micro-fractures/fissures with respect to in- or out-diffusion processes. This will include whole-rock measurements of the U-decay series, ^{37}Cl, ^{11}B, ^{86}Sr and ^{87}Sr along profiles perpendicular to the fracture intersection with the drillcore,
- simple leaching of drillcore material using distilled water,
- scoping study to locate further examples of low transmissive features already characterised to increase the hydrogeological/hydrochemical database, and
- eventual sampling of borehole Section 2 (and possibly a second sampling of Section 4) when indications show that enough water has accumulated.

3.9 The Task Force on modelling of groundwater flow and transport of solutes

3.9.1 Background

The work within the Äspö Task Force constitutes an important part of the international co-operation within the Äspö Hard Rock Laboratory. The group was initiated by SKB in 1992 and is a forum for the organizations to interact in the area of conceptual and numerical modelling of groundwater flow and transport. The work within the Task Force is being performed on well-defined and focused Modelling Tasks and the following have been defined so far:

- **Task No 1:** The long term pumping test (LPT-2) and tracer experiments. Site scale.
- **Task No 2:** Scoping calculations for a number of planned experiments at the Äspö site. Detailed scale.
- **Task No 3:** The hydraulic impact of the Äspö tunnel excavation. Site scale.
- **Task No 4:** Modelling of radionuclide transport in a hydraulic feature based on data from the Tracer Retention and Understanding Experiment ,1st stage (TRUE-1). This involves non-reactive and reactive tracer tests at a detailed scale of 5 m.
- **Task No 5:** Impact of the tunnel construction on the groundwater system at Äspö, a hydrological and hydrochemical model assessment exercise. It is conducted at the site scale of about 1km.

- **Task No 6:** Apply performance assessment (PA) and site characterization approaches for the same tracer experiment and PA boundary conditions. Aims at identifying relevant conceptualisations for longer term PA predictions and identify site characterisation data requirements to support PA calculations. This task was approved for initiation during 2001.

During 2000 eight foreign organisations in addition to SKB were participating in the Äspö HRL Task Force. These organizations are: Japan Nuclear Cycle Development Institute (JNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI), Japan; Agence National pour la Gestion des Déchets Radioactifs (ANDRA), France; POSIVA Oy, Finland; Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA), Switzerland; Bundesministerium für Wirtschaft und Technologie (BMWi), Germany; Empresa Nacional de Residuos Radiactivos (ENRESA), Spain and US DOE/ Sandia National Laboratories.

3.9.2 Objectives

The Äspö Task Force is a forum for the organizations supporting the Äspö HRL 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. The Task Force interacts with the *Principal Investigators* responsible for carrying out experimental and Modelling work for the Äspö HRL in areas of particular interest for the members of the Task Force.

3.9.3 Results

Modelling for Task 1–3 were completed in previous years. Results are presented for Task 4 and 5 only.

Task 4

Work was undertaken within sub-task E and F which both concerned modelling of the same geometrical configuration of a dipole test but with different flow rates.

Deconvolution of breakthrough curves in Task 4F

To evaluate the breakthrough curves excluding the effects caused by the injection procedure a mathematical treatment of the tracer test data can been done. This treatment, called deconvolution, uses the experimental tracer injection curves and breakthrough curves to evaluate what the breakthrough curve would have looked like if the injection was performed as a pulse with unit mass and zero duration (Dirac function). Ideally, all features of the resulting curve – the unit response function – are caused by processes occurring during the transport. In reality experimental errors may cause oscillations or mathematical artefacts in the unit response function. Therefore, mathematical manipulation of the experimental curves in the form of smoothing or curve fitting may be needed.

Deconvolution of experimental breakthrough curves using the injection curve in order to obtain a unit response function is a useful approach to evaluate tracer experiments in order to identify features in the breakthrough curves caused by transport processes and not caused by the shape of the injection curve. In particular they can be used for comparison with unit response functions obtained from model predictions.

For the STT-2 test which was modelled in Task 4E and 4F the double peak present in the breakthrough curve remains in the unit response function after deconvolution. This is an indication that the double peak is not an effect of the injection procedure, but an effect due to the presence of multiple pathways during the tracer test.

The method presently used for deconvolution has successfully deconvoluted all of the tracers used in the STT-2 test. However, there is a need for further improvement of the method in order to obtain a better resolution for non-sorbing tracers and to handle curves with oscillations due to large experimental errors.

This work is reported in Elert and Svensson /2001/.

Task 5

The modelling task consists of: a) predicting water composition expressed as mixing proportions of water types at selected control, b) predicting hydraulic head in selected boreholes and c) making an assessment of the chemical evolution during tunnel construction. The modelling was completed during the year and draft final reports were produced.

A Task Force Meeting was held in Carlsbad, NM on February 8–11 /Morosini, 2000/.

3.10 Colloids

3.10.1 Background

Colloids are small particles in the size range 10^{-3} to 10^{-6} mm these colloidal particles are of interest for the safety of spent nuclear fuel because of their potential for transporting radionuclides from a defect repository 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 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 large attachment factor to the rock which reduces stability and the transport capacity of the colloids in the aquifer.

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 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 /Kertsting et al, 1999/. Based on these results SKB decided year 2000 to initiate the project COLLOIDS at Äspö-HRL to study the stability and mobility of colloids. The project will run during the time period 2000–2002.

3.10.2 Objectives

The objectives of the colloid project is to:

1. Study the role of bentonite clay as a source for colloid generation.
2. Verify the colloid concentration at Äspö-HRL.
3. Investigate the potential for colloidal transport in natural groundwater flow paths.

3.10.3 Experimental concept

The experimental concept for the Colloid project is: laboratory experiments, background measurements and fracture specific measurements. These concepts are described below:

Laboratory experiments: The role of the bentonite clay as a source for colloid generation at varying groundwater salinities (NaCl/CaCl) will be studied in a laboratory experiment performed at KTH (Royal Institute of Technology) and at the company Clay Technology (Figure 3-36).

Background measurements: The background colloid concentration associated with the different water types found at Äspö will be sampled at specific locations along the Äspö HRL-tunnel. The colloid content will be 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 (Figure 3-37). The advantage is that the resolution of this equipment is higher compared with standard equipment. It is therefore possible to detect the colloid contents at much lower concentrations than previously possible. The outcome of these measurements will be compared with standard type of measurements such as particle counting by using Laser Light Scattering (LLS) at KTH and at INE. Standard type of filtration performed on-line at the boreholes are used in order to be able to compare/transform these results to all the earlier colloid sampling campaigns at Äspö.

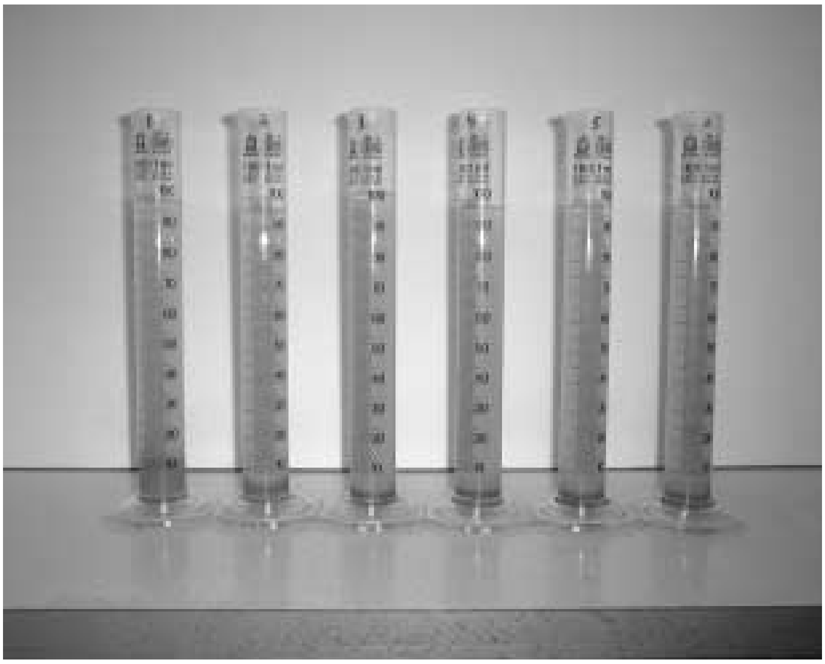


Figure 3-36. *The salinity of the water may affect the colloid generation. The experiment show different degrees of sedimentations of bentonite clay dependent of the ion content (NaCl) in the water. A very high or low ion content may result in bentonite instability and colloid generation.*

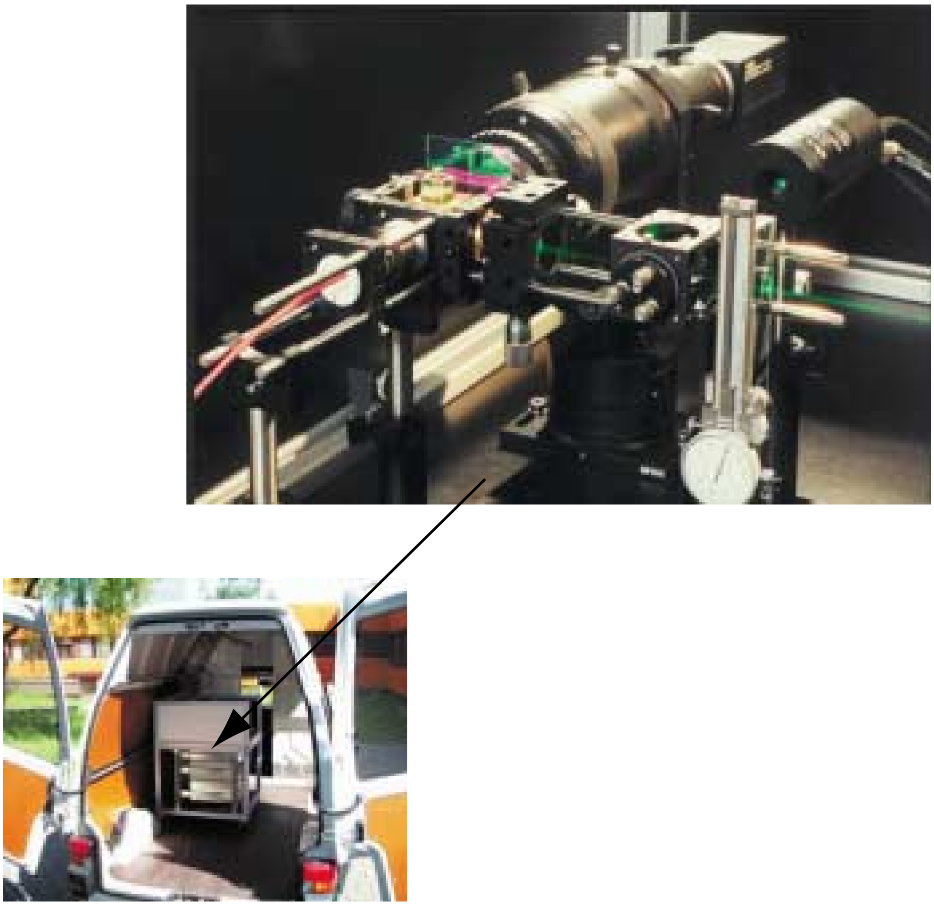


Figure 3-37. Equipment for Laser-induced Breakdown-Detection (LIBD) of colloids (upper picture). The equipment is installed in a van in order to allow mobility and on-line measurements (lower picture).

Fracture specific measurements: For the fracture specific measurements two nearby boreholes at HRL will be selected for the experiment. One of the boreholes will be used as an injection borehole and the borehole downstream will be used as a monitoring borehole. The boreholes intersect the same fracture and have the same basic geological properties. After assessing the natural colloid content in the groundwater bentonite clay will be dissolved in ultra pure water to form colloidal particles. These clay colloids will be labelled with uranine, a water conservative tracer. The mixture will be injected into the injection borehole (Figure 3-38). From the monitoring borehole the colloidal content will be measured with laser (LIBD/LLS), the water will be filtered and the amount of tracers will be measured.

The following results are of interest 1) is the bentonite clay a potential source for colloid generation and, 2) is the colloid content lower after transport. The outcome of the experiment is used to check the calculations in the safety assessment report such as TR 91-50 and to be used in future colloid transport modelling.

3.10.4 Scope of work for 2000

The scope of the work for 2000 contained planning and preparation work for the project.

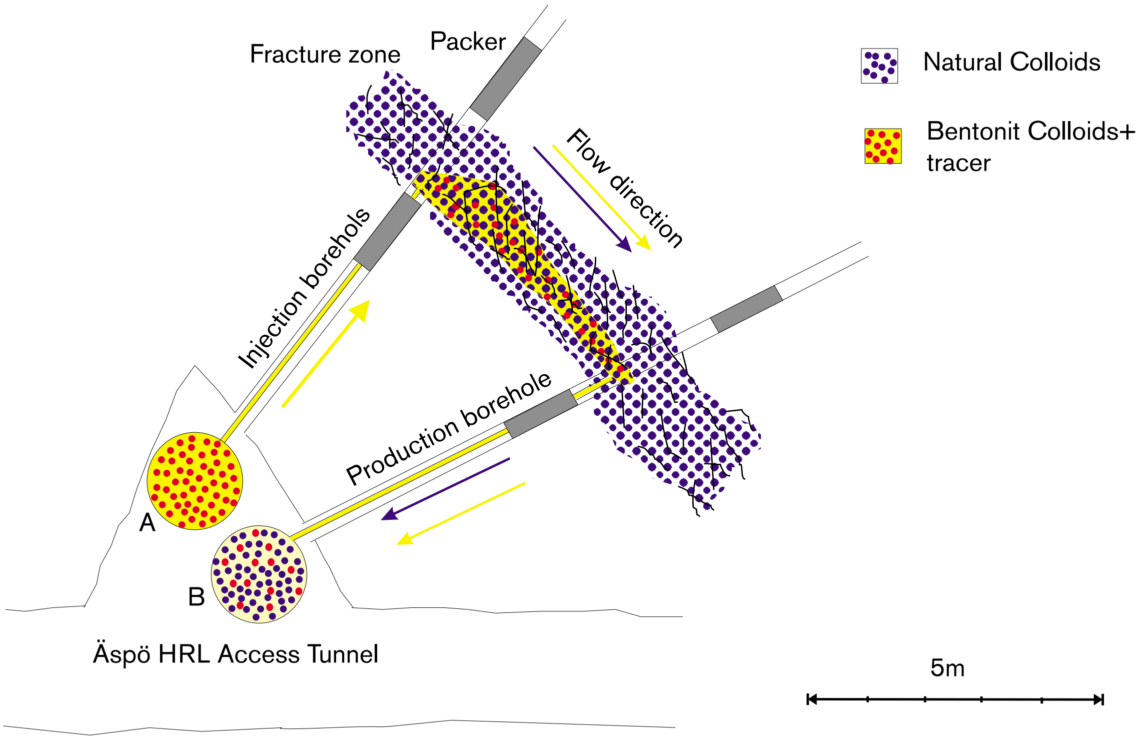


***Figure 3-38.** Injection of bentonite colloids and a tracer at the injection borehole and monitoring of the injected and natural colloids in the production borehole.*

3.11 Microbe

3.11.1 Background

A set of microbiology research tasks for the performance assessment of high level radioactive waste (HLW) 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, such as those at MICROBE.

3.11.2 Objectives

The major objectives for the MICROBE site 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 microorganisms 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.

3.11.3 Experimental concept

The objectives above 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. An in situ site allows experiments at natural pressure with relevant gas content in groundwater, which is of great importance for microbial activity and very complicated to obtain in vitro. Such a site was drilled in May 1999 in the J-niche at Äspö HRL, 450 m underground. The J-niche tunnel has a largest diameter of 9 m and is located at about 450 m depth. The length of the niche is 20 m. Three boreholes were produced for MICROBE. Two additional boreholes have been drilled in the J-niche for CHEMLAB. Groundwater data from those two adjacent boreholes have been included in the results for comparison.

Drilling of the MICROBE boreholes followed an established quality plan using steam and alcohol cleaning to minimize potential contamination. Triple-tube drilling technique with the use of a core retriever was used to minimise the exposure of the core to drill water and to deliver the core intact, also when multi-fractured rock is penetrated. The drill tube protected the drill core from contact with aquifer systems intersected during drilling. A split tube keept intersected fractures intact, with also small pieces of rock in their original place.

The MICROBE boreholes are instrumented with packers that do not expose metal to the groundwater. It was deemed important to have the smallest possible void volume in the packer systems. One water-conducting feature was found in each of the MICROBE boreholes. They have been sectioned off with a double packer with a sealing length of 1000 mm per packer. The material chosen for the hard body parts was PEEK.

A system that allows circulation of groundwater under full formation pressure is presently being designed (Figure 3-39). This system should enable work with microbes at very close to in situ conditions. It is planned to be operative early summer 2001.

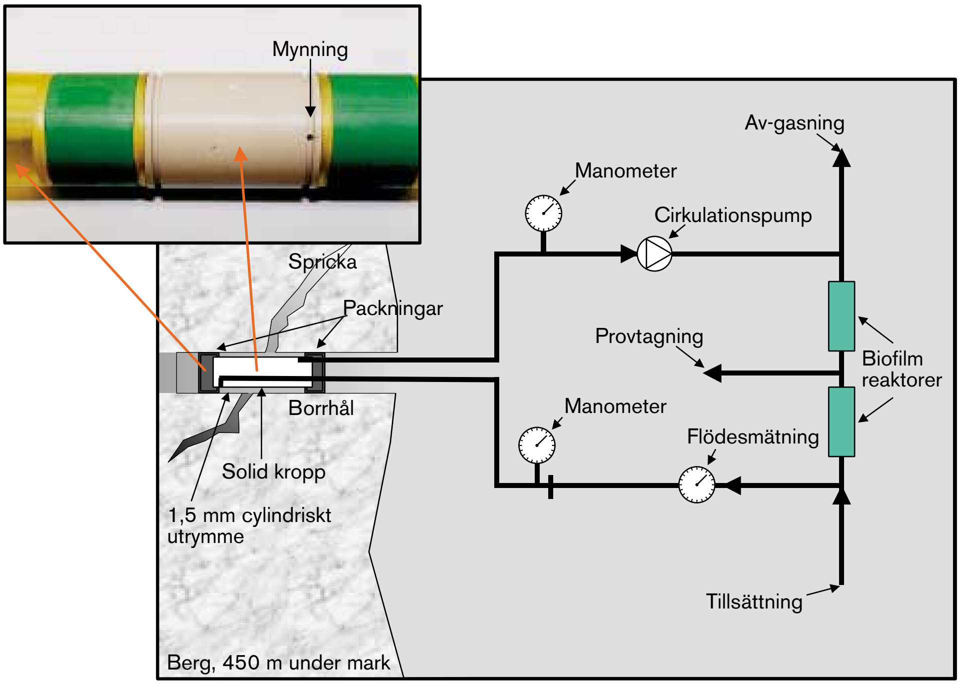


Figure 3-39. *The circulation system at MICROBE.*

A system for sensible measurement of hydrogen and other reducing gases will also be developed. A reduction gas detector will be applied, having a detection limit for hydrogen, carbon monoxide and methane close to 1 part per billion. This system will be used for characterisation of hydrogen generation and flow in granitic rock environments. The results will be compared with theoretical calculations performed at KTH, Stockholm. The site will enable a continuation of buffer tests /Pedersen et al, 2000/, including a study of the potential for microbial copper corrosion at repository conditions. The planned start for those experiments is spring 2001. Installation of biofilm reactors in the circulation system is planned for investigations of radionuclide retention experiments.

3.11.4 Results

The main activity for the MICROBE site year 2000 has been to characterize the chemistry and the microbiology of the groundwater in the drilled boreholes.

3.11.5 Groundwater chemistry

Groundwater was sampled and chemical analysis was performed according to the Class V protocols. Results on the chemical main constituents, environmental isotopes, stable isotopes of gases and trace elements of the groundwater have been recently reported /Pedersen, 2000/. The contents of gas and the amounts of specific gases are central for the fulfilment of the objectives and the results are shown in Table 3-4. The nitrogen content has a position in the middle of the range of gas data obtained in groundwater from the Fennoscandian shield, while argon lies among the lower and helium among the higher values obtained /Pedersen, 2000/. Carbon dioxide and hydrogen also have average positions in the ranges while methane is in the upper part of the range observed.

Table 3-4. The amount and content of gases in the J-niche boreholes.

Borehole	Volume gas ml/L	N_2 ml/L	H_2 µl/L	He ml/L	Ar ml/L	CO_2 ml/L	CH_4 ml/L	C_2H_2 µl/L	C_2H_4 µl/L	C_2H_6 µl/L	C_3H_6 µl/L	C_3H_8 µl/L
CHEMLAB	91	77.6	6	9.27	0.78	0.37	0.92	<0.05	<0.05	0.3	<0.09	<0.09
MICROBE	83	70.7	<3	7.46	0.70	0.66	0.77	<0.05	<0.05	0.3	<0.09	<0.09
MICROBE	81	70.0	<3	7.42	0.80	0.20	0.63	<0.05	<0.05	0.2	<0.09	<0.09
CHEMLAB	55	44.1	10	7.0	0.78	0.75	1.10	<0.03	<0.03	0.2	<0.06	<0.06
MICROBE	78	66.8	16	5.95	0.69	0.95	1.2	<0.04	<0.04	0.2	<0.08	<0.08

MICROBE shows a gas content and composition that is representative for many other groundwater sites tested. MICROBE is thereby well suited for the objectives concerning gas related tasks.

3.11.6 Microbiology

The groundwater to be analysed was collected directly from the borehole tubing after sampling for chemistry. This gave the requested flushing of a borehole before microbiology sampling. The sample was transferred directly to anaerobic glass serum bottles for further preparation in the laboratory on the surface. To ensure the efficiency of the equipment sterilization, control samples were analysed. These were sample bottles and the media used. Sterile water was sampled as control water and processed as samples. MICROBE shows a microbial diversity that is representative for many other groundwater sites tested. MICROBE is thereby appropriate for the objectives.

Table 3-5. The results from direct counting of total number of microbes with epi-fluorescence microscopy and viable (culturing) counting of microbes in the packed off MICROBE borehole sections.

Borehole	Total number microbes	Iron reducing bacteria	Sulphate reducing bacteria	Hetero-tropic acetogens	Auto-trophic acetogens	Hetero-trophic methanoges	Auto-trophic methanogens
				cells/ml			
KJ0050F01	14000	24	360	24	<0.1	<0.1	<0.1
KJ0052F01	2300	2.3	9.4	24	<0.1	<0.1	<0.1
KJ0052F03	20000	36	1100	0.23	0.26	<0.1	<0.1

3.11.7 Principal component analysis of groundwater chemistry results

Results from Principal Component Analysis (PCA) analysis /Laaksoharju et al, 1999/ based on the MICROBE data set together with geochemical data from many other Fennoscandian shield sites are shown in Figure 3-40. The constituents used for the modelling were the major components (Na, K, Ca, Mg, HCO_3, Cl and SO_4), tritium (^3H) and stable isotopes (δ^2H and $\delta^{18}O$). It is known that these components contain most of the variability of the information in groundwater data. The variability for the first and second principal components shown in Figure 3-40 is 70% which means that the first and second principal components summarize 70% of the groundwater data information. The weight for the different elements is shown in the equations for the first and second principal components respectively. From these weights the importance of the individual elements for the total analysis can be tracked. The MICROBE (and CHEMLAB) groundwater samples plot in the middle of Figure 3-40, showing that those waters do not have an extreme groundwater composition and that the samples are affected by mixing of several reference waters.

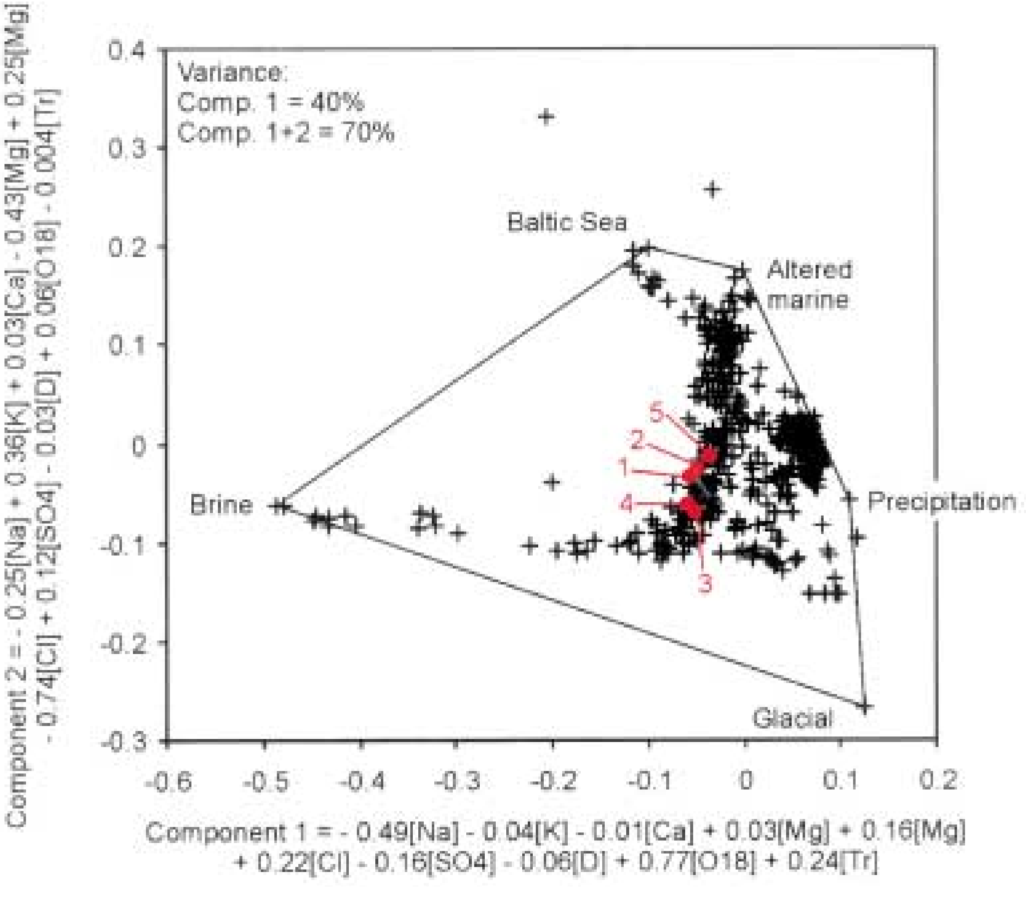


Figure 3-40. *Principal component plot showing groundwater chemical data from the MICROBE and CHEMLAB sites (red) in comparison to data from Fennoscandian field sites (black +). The samples from the investigated sites plot in the middle of the PCA-plot indicating that these waters may be affected by a possible mixing contribution from several reference waters such as glacial, brine and precipitation. 1 and 4 are CHEMLAB boreholes, 2, 3 and 5 are the MICROBE boreholes.*

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

4.1 General

Stage goal 4 of the 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, is conducted under realistic conditions and at appropriate scale. A number of large-scale field experiments and supporting activities are therefore in different phases of planning, installation or operation at the Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing, and will together form a major experimental programme.

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

- To furnish methods, equipment and procedures required for excavation of tunnels and deposition holes, near-field characterisation, canister handling and deposition, backfilling, 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, 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.

4.2 The Prototype Repository

4.2.1 Background

Many aspects of the repository concept (KBS-3) have been tested in a number of in-situ and laboratory tests. Models have been developed that are able to describe and predict the behavior 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 during 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 and in full-scale and to demonstrate that it is possible to understand and qualify the processes that takes 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 Äspö Prototype Repository is a dress rehearsal of the action needed to construct a deep repository from detailed characterisation to resaturation of deposition holes and backfilling of tunnels. The Prototype Repository is focused on testing and demonstrating the system function of the KBS-3 concept and will 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.

Activities aimed at contributing to development and testing of practical engineering measures to rationally perform the steps of a deposition sequence are included. Efforts in this direction are limited since handling can not be made as in a real deep repository. However, it is believed that experience on handling will be gained to some extent. Handling matters are further addressed in other project such as Technology Demonstration and Canister Retrieval Test.

4.2.2 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 operation stage in the real deep repository. The Prototype Repository will in this context provide operating experience for 10–20 years longer than have been achieved with deposited canisters containing spent fuel.

4.2.3 Experimental concept

The Prototype Repository is set up to simulate a part of the KBS-3 type repository under what can be described as normal conditions, which is essentially the same as the reference scenario described in Research, Development and Demonstration Programme 98. The Prototype Repository is planned to simulate, to the extent possible, the real deep repository system, regarding geometry, materials, and rock environment. The test arrangement is planned to 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.

Important limitations with respect to the possibilities to simulate a repository situation are:

- The test site area is given and the location in conjunction with certain conditional criteria is therefore limited.

- No spent fuel, or any other form of nuclear waste, will be used. Canisters equipped with electrical heaters will be used to simulate encapsulated spent fuel.
- The Prototype Repository cannot demonstrate long-term safety, since the experiment considered will be extended in time at most tens of years.

In the deep repository, the plan is that localisation of the repository, deposition tunnels and final canister positions shall be determined by a step-by-step characterisation system followed by a detailing of the repository layout. Each step is based on data from characterisation of the host rock, which contribute to adjustment of localisation in relation to data as major and minor discontinuities and their orientation, water conditions, magnitude and orientation of rock stresses etc. The site of the Prototype Repository is given. However, methods for characterisation of the rock mass in the test site are expected to contribute to the assessment of methods for characterisation of the rock mass and the canister positions in a real deep repository.

Different alternatives as regards location and layout of the Prototype Repository have been considered. The test location chosen is the innermost section of the TBM tunnel at 450 m depth. The layout involves six deposition holes with a centre distance of 6 m (Figure 4-1). The distance is evaluated considering the thermal diffusivity of the rock mass and a maximum temperature of 90°C on the canister surface.

The deposition holes have been mechanically excavated by full-face boring, diameter 1.75 m and to a depth of 8 m. Performance of the boring machine and the boring technique has been analysed. Special considerations have been taken to investigate the geometric results, surface roughness, and the disturbed zone (EDZ) i.e. induced fracturing.

A massive concrete plug designed to withstand full water- and swelling pressures will separate the test area from the open tunnel system. A second plug will be placed such that it divides the test into two sections, comprising four and two canister holes. This layout will in practice provide two independent test sections with the advantage that the outermost one can be dicommissioned without disturbing the testing in the inner one.

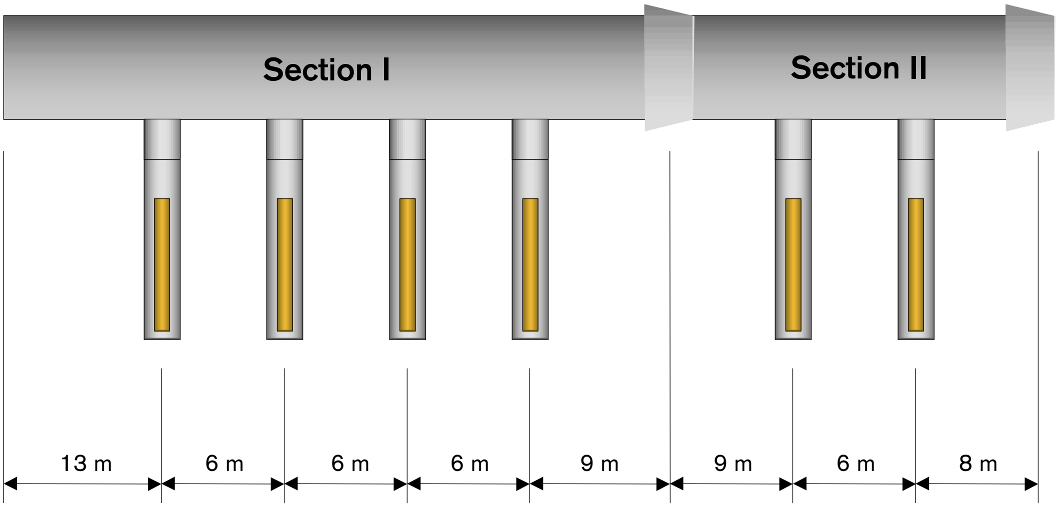


Figure 4-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

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. The plan is that decay heat will be controlled by real power output.

The buffer surrounding the canisters will be made of highly compacted Na-bentonite blocks, (Figure 4-2). The blocks will fill up the space between the rock and the canister but leave an outer slot of about 50 mm and a 10 mm slot between the blocks and the canister. The blocks will be made in full diameter 1.65 m and with a height of 0.5 m. The outer slot is planned to be filled with bentonite pellets and water as part of the deposition process. The final average density of the buffer in the deposition holes after water saturation will be about 2 ton/m^3 which represent a confined swelling pressure of approximately 5 MPa. The deposition tunnel will be backfilled with a mixture of 30% bentonite (Na-concerted Ca-bentonite) and 70% crushed rock; 10–15% Na-bentonite being the normal grade in fresh water.

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 (Section II) will be decommissioned after approximately five years to obtain interim data on buffer and backfill performance through sampling. The inner section (Section I) will be designed for an operational life time of 20 years.

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

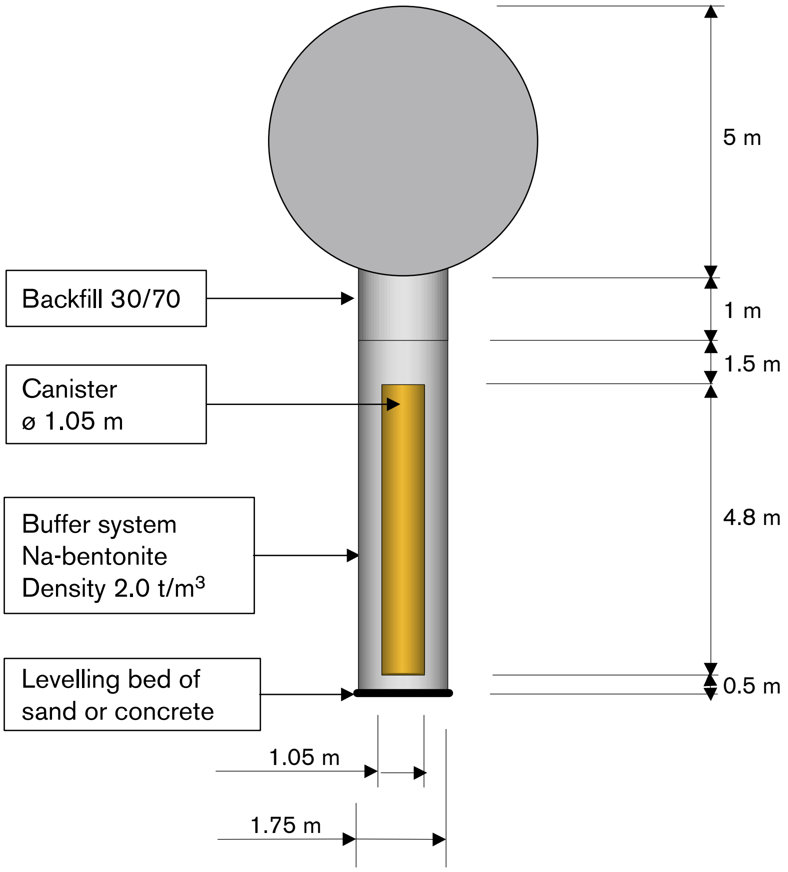


Figure 4-2. *Schematic layout of the deposition holes (not to scale).*

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.
- Chemical processes in rock, buffer and backfill.
- Bacterial growth and migration in buffer and backfill.

4.2.4 Results

Characterisation

During the period inflow measurements into the prototype tunnel, to the deposition boreholes and to the lead-through boreholes between tunnel A and tunnel G have been made, see Figure 4-3. In one deposition hole detailed inflow observations were mapped. The pressure responses were observed during the drilling of the deposition- and lead-through boreholes and four pressure build-up tests were made in the three lead-through boreholes. Pressure observations were also made during blasting work in the Prototype Repository Tunnel. A few results are presented below and details can be found in Forsmark et al /2001/.

The result of the inflow measurements to the Prototype Repository tunnel is shown in Table 4-1.

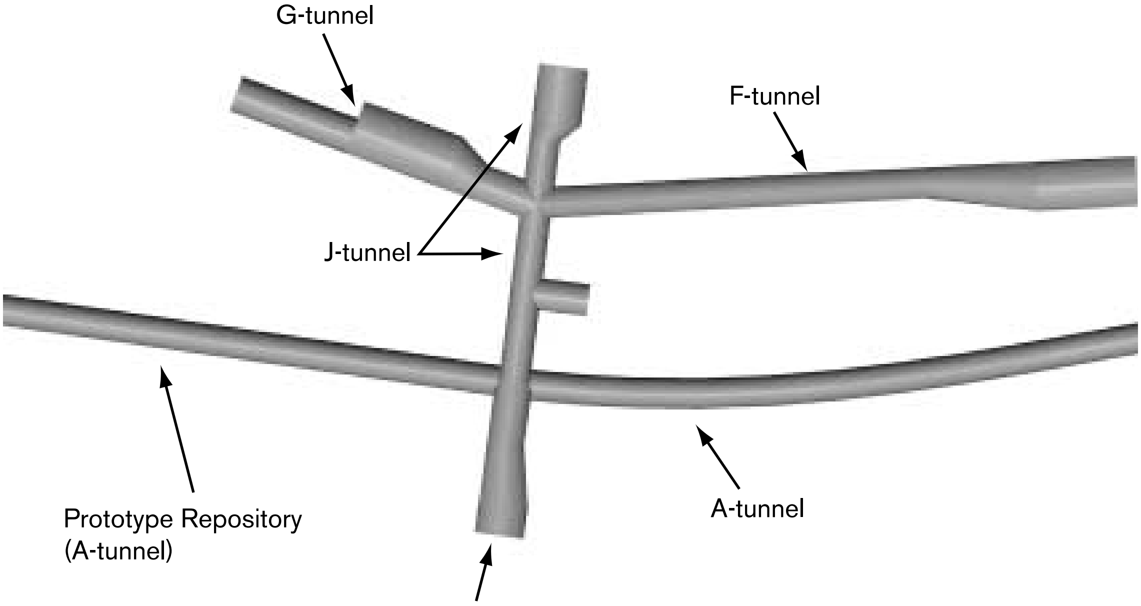


Figure 4-3. *Tunnel systems close to the Prototype Repository.*

Table 4-1. Result of inflow measurements to Prototype Repository tunnel.

Weir sections 1997 (m)	Q 1997 (l/min)	Weir sections 1999 & 2000 (m)	Q 1999-12-01 (l/min)	Q 2000-03-30 (l/min)
3527 – 3533	0.20	–	–	–
3533 – 3539	1.17	–	–	–
3539 – 3545	0.12	–	–	–
3545 – 3551	0.03	–	–	–
3551 – 3557	0.02	–	–	–
3557 – 3562	0.05	–	–	–
3562 – 3568	0.10	3546 – 3552	0.001	0.006
3568 – 3575	0.05	3552 – 3570	0.100	0.110
3575 – 3581	1.56	3570 – 3576	0.000	0.000
3581 – 3587	1.61	3576 – 3582	2.000	1.320
3587 – 3593	0.29	3582 – 3588	1.490	1.820
3593 – 3600	0.93	3588 – 3600	1.120	1.080
SUM (3545–3600)	4.84	SUM (3546–3600)	4.711	4.336
SUM (3527–3600)	6.13			

The measurement sections are not exactly the same and it is therefore not possible to be certain about the flow rate changes for the passed time. However, the flow rate to section 3545–3600 and 3546–3600 are approximately the same during 1997, 1999 and 2000. Comparing the individual sections between 3545 to 3600 indicates that possibly all sections, but 3576–3582 and 3582–3588 m have slowly decreasing flow rates. In sections 3576–3582 and 3582–3588 m the flow rate changes rather much between the measurements, possibly due to changes of the flow rates from the flowing features.

In Table 4-2 the result of the whole borehole inflow measurements in the deposition boreholes is shown. The in-leakage rates are small, as can be seen in the table. Due to the small rates it was difficult to measure the inflow.

Table 4-2. Result of inflow measurements to deposition boreholes. Flow measurements were made December 1999, March 2000 and June-July 2000. The figures in the table represent what is considered to be the best estimates.

Deposition hole	Q 1999-12-08 – 1999-12-13 (L/min)
DA3587G01	0.08
DA3581G01	0.002
DA3575G01	0.003
DA3569G01	0.0007
DA3551G01	0.002
DA3545G01	0.003
SUM	0.097

In order to get an idea of the variations of in leakage to a borehole, measurements using ordinary diapers applied to the borehole walls of DA3581G01 were made during the summer of 2000. Figure 4-4 shows the result graphically.

The only visually mapped water bearing structure in this borehole is located beneath a plank. Since the diapers closest to it quickly became close to fully water saturated and part of the fracture is outside the diaper, excess water flowed downwards on both sides of Z plank. Due to this, below the measuring points for the water bearing structure the flow rate shown in Figure 4-4 may be too high.

As can be noticed in Figure 4-4 the inflow is located to the parts of the borehole, which has earlier been mapped as an area with water-bearing features. Still inflows exist in a more diffuse pattern in large parts of the borehole walls, even if those parts have not and could not be mapped as water-bearing parts.

The drilling of lead-through boreholes from tunnel G to tunnel A confirms the, during earlier investigations, indicated pattern of a hydraulically dominant response direction running WNW.

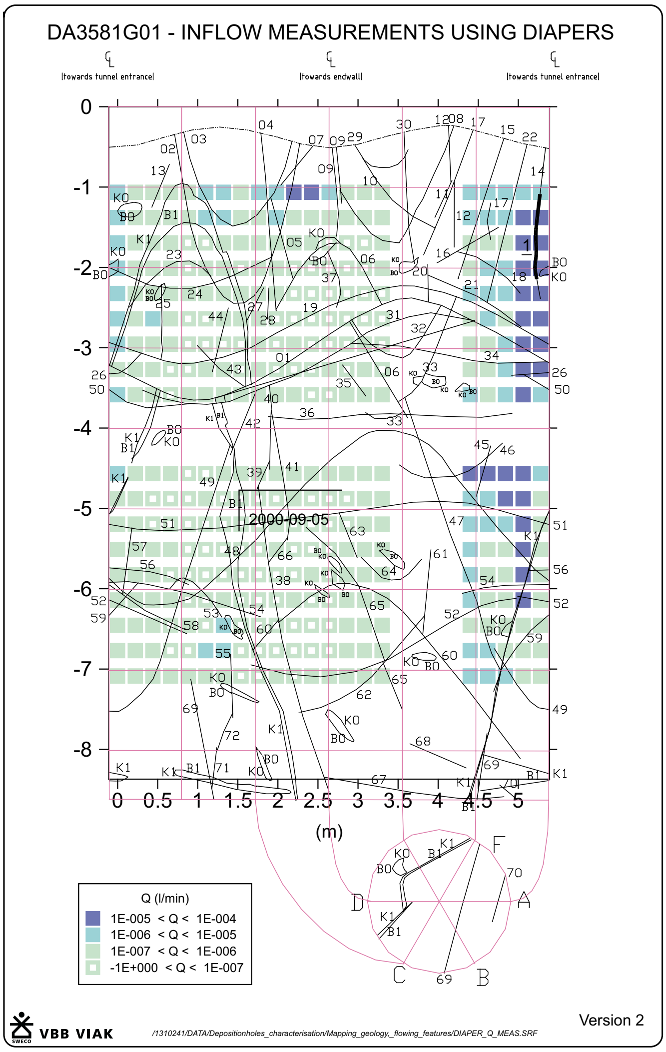


***Figure 4-4.** Inflow measurements in DA3581G01 using diapers.*

In the preparations for the concrete plug construction, blasting of niches were made at two chainage locations in the Prototype Repository tunnel, namely 3537 and 3560. Pressure response registrations were made in boreholes KA3510A, KG0021A01 and KG0048A01 during the blasting period, 2000-08-24 – 2000-09-05.

A result is that at several blasting occasions the pressure rises in the observation sections after almost every blasting round. An example is given in Figure 4-5. At the most the increases were approximately 8–10 meters in four out of five sections in KG0021A01 observed during the first blasting round. In KG0048A01 the corresponding pressure increase was 1–4 meters in all four sections. The pressure increase seems to be somewhat higher for sections closer to the constructed niche.

These measurements clearly show that the blasting affects the hydraulic system. A probable cause is that the vibrations from the blasting make the gauge material in the fracture move. The inter-connected fracture system will then become less permeable and the pressure will increase in the fracture systems up-gradient of the clogged fractures.

The pressure increase after each blasting round is of the similar magnitude in several sections indicating the possibility of the clogging of major flowing features.

Pressure changes due to blasting have also earlier been observed during other excavations in the Äspö HRL.

Monitoring

During the characterisation of the rock around the Prototype Repository a large number of boreholes has been drilled. These bore holes will be equipped with packer systems to allow for:

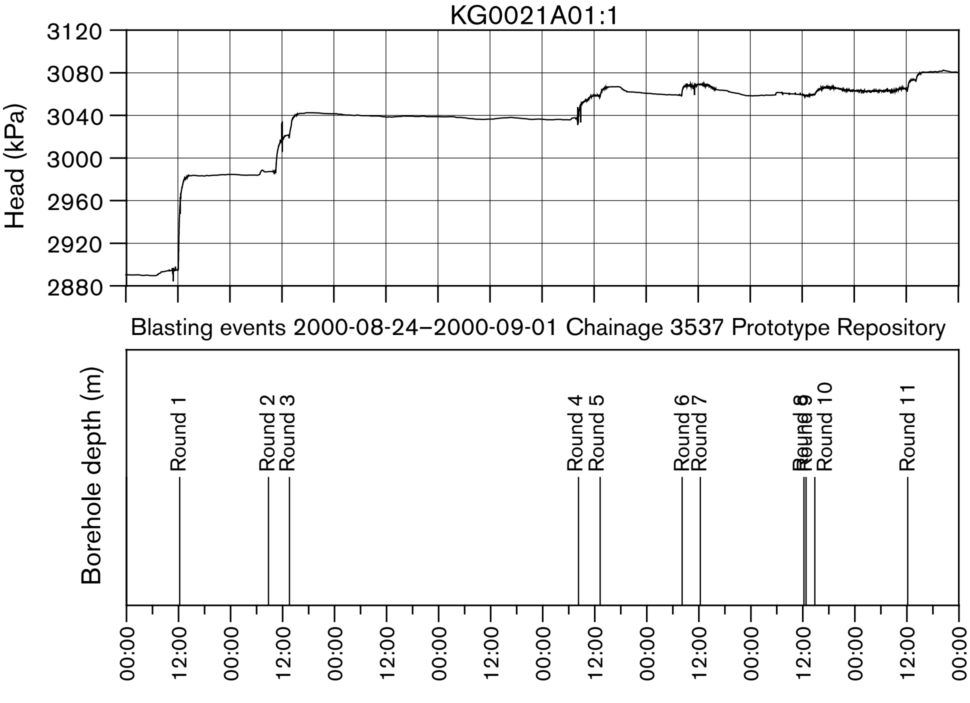


Figure 4-5. Example of pressure response due to blasting.

- Pressure measurements.
- Water sampling (mostly in Section I).
- Dilution measurements.
- Interference tests.
- Hydromechanical measurements and tests (Section II).

For the monitoring in boreholes bentonite packers, see Figure 4-6, have been developed and tested. These will be used in Section I in all boreholes except for the shortest where mechanical packers will be used.

Modelling

A second DFN model has been made based on data from the tunnel and the drilled boreholes for characterisation. Predictions were made of the flow into the deposition holes, the fracture statistics in the deposition holes and pressures around the tunnel. The modellers had no information about the actual outcome. An example of prediction is the predicted average conductive fracture frequency: P_{21} = 0.79 to 1.08 m/m^2 based on 20 realisations. A few results are presented in Figure 4-7. The predictions will be compared to the measurements during spring 2001.

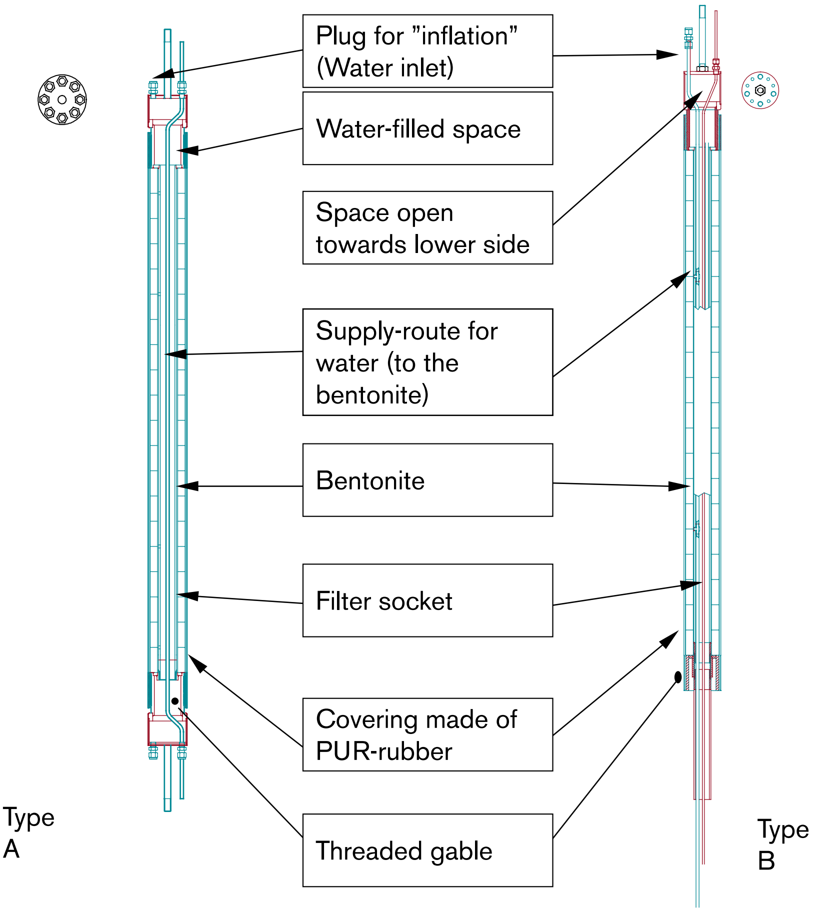


Figure 4-6. *Drawing of the bentonite packer.*

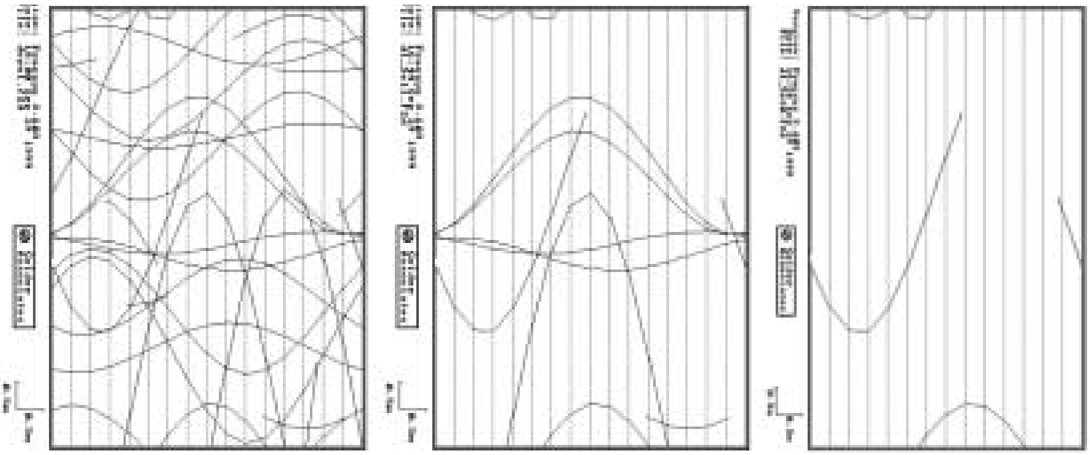


Figure 4-7. An example of the predicted fracture traces in a deposition hole. Left figure: All fractures. Middle figure: Natural fractures (Open fractures, T>5·10^{-11} m^2/s), Right figure: Conductive fractures (T>5·10^{-10} m^2/s).

4.2.5 EU-project

In September the EC contract was finalised and signed for a period of 42 months, i.e. through February 2004. The participating organisations are:

- SKB (Svensk Kärnbränslehantering AB) – Co-ordinator
  - GeoDevelopment AB
  - VBB VIAK AB
  - Clay Technology AB
- POSIVA (Posiva Oy)
  - VTT (VTT Communities & Infrastructure)
- ENRESA (Empresa Nacional de Resíduos Radioactivos SA)
  - AITEMIN (Asociacion para la Investigacion y Desarrollo Industrial de los Recursos Naturales)
  - CIMNE (Centre Internacional de Mètodes Numèrics en Enginyeria)
- GRS (Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH)
- BGR (Bundesanstalt für Geowissenschaften und Rohstoffe)
- UWC (University of Wales, Cardiff)
- JNC (Japan Nuclear Cycle Development Institute)

The kick-off meeting was held at Äspö on September 14–15, 2000, and the first modelling meeting on December 12, 2001 in Lund.

4.3 Demonstration of Disposal Technology

4.3.1 Background

SKB decided 1996 that the all transport and handling of the copper canister with spent fuel from the encapsulation plant to the deep repository should be carried out with full radiation shielding. Also the handling of the canister in the deposition tunnel should be done with full radiation shielding. A feasibility study for the development of a full size deposition machine started late 1996 and a number of different concepts were investigated. Mid 1997 the preferred concept for the deposition machine was selected and the work with conceptual design and engineering design of the deposition machine started. Early 1998 the manufacturing drawings and specifications for the main parts of the machine was completed and could be ordered for manufacturing.

The assembly of the deposition machine for testing on a test bed at the manufacturing workshop started in December 1998. The workshop tests were completed in May 1999. The deposition machine was transported to the Äspö HRL in June 1999 and installed in a tunnel prepared with four deposition bore-holes at level 420 m below ground. This tunnel will also be used as an exhibition hall for information about the Swedish Waste Management Programme.

The development of the equipment needed for the handling of the buffer material and canisters with heaters for the two planned engineering experiments at Äspö HRL, the Canister Retrieval Test and the Prototype Repository, has been ongoing in parallel.

Objective

The main objective with the ongoing work is to develop and demonstrate the techniques and equipment needed for handling and deposition of the buffer material and copper canister with spent fuel as well as the emplacement of the backfill material and sealing of the deposition tunnels.

Results

The full size deposition machine for deposition of copper canisters was installed during 1999 and will be used for demonstration at Äspö HRL. The picture in Figure 4-8 below shows the deposition machine in the demonstration tunnel at Äspö in May 2000.

Main data for the machine:

Height	4.6 m
Width	3.7 m
Length	11.8 m
Weight, empty	90 tons
Weight, with shielded tube and canister	140 tons
Speed	1–10 m/min
Power supply	Cable
Capacity, main hoist	30 tons
Capacity, auxiliary hoist	5 tons
Capacity, hoist for bentonite top block inside machine	1 ton

Figure 4-8. *Picture of the deposition machine in the demonstration tunnel at Äspö.*

The design and testing of temporary equipment for handling and deposition of the buffer material and canisters for the Canister Retrieval Test and the Prototype Repository was completed early 2000.

The gantry crane with tools for emplacement of the bentonite buffer into to deposition hole and the small deposition machine that will be used for these experiments. The gantry crane and the handling tool for the full size compacted bentonite blocks and rings are shown in Figure 4-9 during the installation of the buffer for the Canister Retrieval Test. During the initial testing of the equipment blocks and rings of concrete were used but also bentonite units were handled during the testing of the equipment. This equipment will also be used in the Prototype Repository during 2001 and 2002.

Development work of the equipment needed in the future deep repository will continue based on experiences from the ongoing work at Äspö. The different machines, transport and auxiliary equipment will be developed to a feasibility or conceptual stage as part of the ongoing design studies of the deep repository. Some of the equipment may later also be designed and constructed and tested at the Äspö HRL for verification of the function and suitability of the equipment.

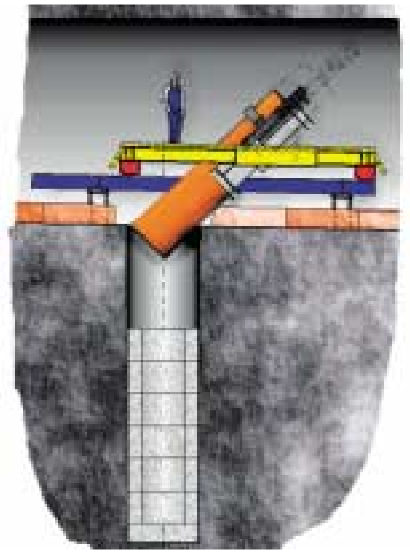
The small deposition machine (Figure 4-10) was used for the deposition of the canister with heaters for the Canister Retrieval Test in August 2000. The small deposition machine will also be used in the Prototype Repository during 2001 and 2002.

The main data and features of the gantry crane are as follows:

Height:	4.3 m
Width:	2.8 m
Length:	8.5 m

Lifting capacity:
Main hoist = 3 metric tons
Auxiliary hoist = 1 metric tons.

Figure 4-9. *Photo of the gantry crane for handling of the compacted buffer material with handling tool for buffer material during testing in June 2000.*



The main data of the deposition machine are as follows:

Height: 3 m
Width: 3.5 m
Length: 8.7 m
Weight: 13 metric tons excluding the copper canister.

The limited height in the prototype repository requires that the canister is tilted down into the deposition hole.

Figure 4-10. *Illustration of the small deposition machine.*

4.4 Backfill and Plug Test

4.4.1 Background

The *Backfill and Plug Test* includes tests of backfill materials and emplacement methods and a test of a full-scale plug. It is a test of the integrated function of the backfill material and the near field rock in a deposition tunnel excavated by blasting. It is also a test of the hydraulic and mechanical functions of a plug. The test is partly a preparation for the Prototype Repository.

The entire test set-up with backfilling casting of the final part of the plug was finished in autumn 1999 and the water saturation, with water filling of permeable mats, started in late 1999. In the year 2000 the water saturation has continued and data from transducers has been collected and reported.

4.4.2 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 test the function.

4.4.3 Experimental concept

Figure 4-11 shows an axial section of the test layout. The test region, which is located in the old part of the ZEDEX drift, can be divided into the following three test parts:

1. The *inner part* filled with backfill containing 30% bentonite (sections A1–A5 and B1).
2. The *outer part* filled with backfill without bentonite and bentonite blocks at the roof (sections B2–B5).
3. 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. Since the crushed rock has no swelling potential but may instead settle with time, a slot of a few dm was left between the backfill and the roof and 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. The remaining irregularities between these blocks and the roof were filled with bentonite pellets.

The two test parts are about 14 meter long and divided 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 nearfield rock. The mats are also used for the water saturation of the backfill. The mats were installed in both backfill parts with the individual distance 2.2 m. Each mat section was divided in three units in order to be able to separate the flow close to the roof from the flow close to the floor and also in order to separate the flow close to the rock surface from the flow in the central part of the backfill.

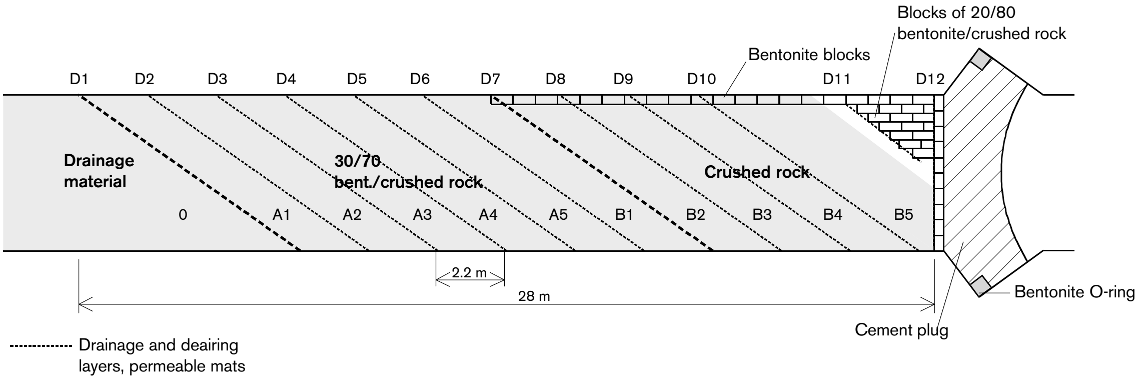


Figure 4-11. An overview of the Backfill and Plug Test.

The outer section ends with a wall made of prefabricated beams for temporary support of the backfill before casting of the plug. Since in situ compaction of the backfill cannot be made in the upper corner, this triangle was instead filled with blocks of bentonite/sand mixture with 20% bentonite content.

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.

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

Figure 4-12 shows a 3D visualisation of the experimental set-up.

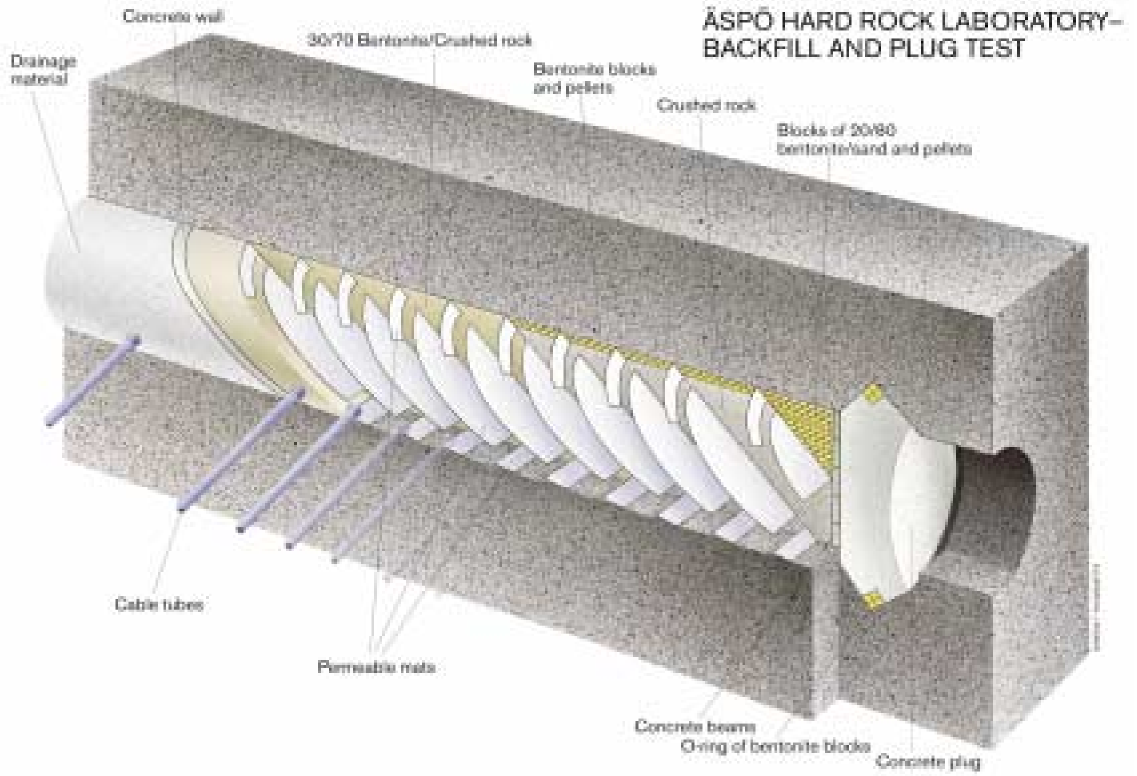


Figure 4-12. *Illustration of the experimental set-up of the Backfill and Plug Test.*

4.4.4 Results

The water saturation of the inner test section (30/70) started on November 29 1999. Every mat in the sections with bentonite/crushed rock has been filled with water with the salt content 1.6% and pressurised with 50–150 kPa. Due to leakage between the bottom filter mats (probably through the fractured floor) the wetting strategy was changed. It was initially decided to fill every second mat and use the mat in-between for de-airing. However, some of the bottom mats, which were intended for de-airing, were due to the leakage filled with water from the neighbouring mats. Therefore all bottom and central mats were filled with water and the top mats used for de-airing.

Water filling of the outer test sections (0/100) started in June and has continued during the rest of the year. The filling is made slowly and stepwise since when the water level is raised water leaks out through the plug between the rock surface and the concrete until the bentonite o-ring has had enough water and time to seal the slot at that level. When the entire bentonite o-ring has sealed or if there is a remaining leakage through another passage in the concrete or rock, the interface between the concrete and the rock surface will be grouted. The plug was not tight in December.

Water saturation, water pressure and swelling pressure in the backfill and water pressure in the surrounding rock have been continuously measured and recorded during the whole year. It seems as we are recieved acceptable data from almost all instruments.

Figure 4-13 and Figure 4-14 show example of measured results. Figure 4-14 shows the water pressure in the rock measured in the short bore holes about 30 cm below the floor of the tunnel. The results show that water has entered the outer section at the same time as water was introduced in the inner section and partly filled before the intentional start of the water filling in the outer section in June.

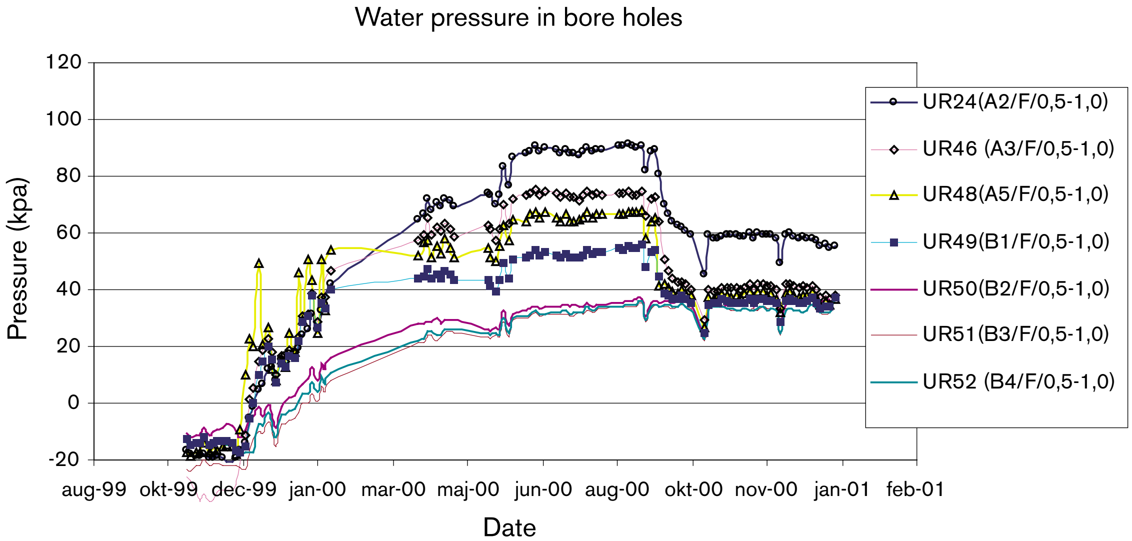


Figure 4-13. *Water pressure measured in the rock 30 cm below the floor UR24, 46, 48 and 49 are placed in the 30/70 sections and the rest in the 0/100 sections.*

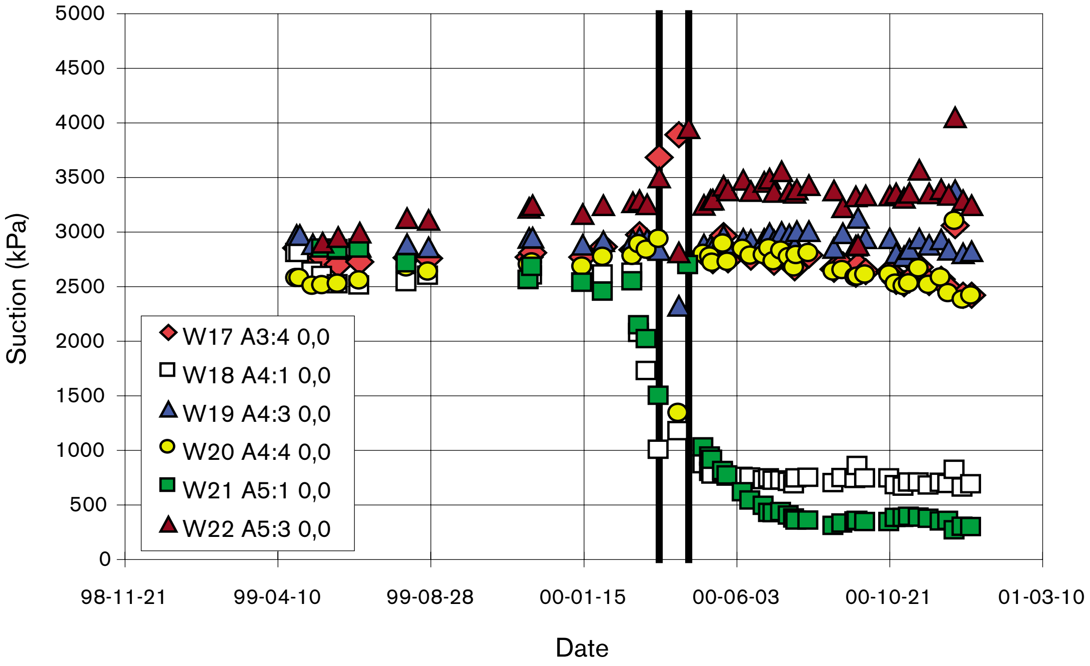


Figure 4-14. *Suction measured in the centre of different layers in the 30/70 backfill. W18 and W21 are placed in the first layer about 20 cm from the mats. W17 and W20 are placed 40 cm and W19 and W22 are placed 60 cm from the mats.*

Figure 4-14 shows the suction (negative pore water pressure) measured with psychrometers in the tunnel centre line in different layers of 30/70. Only the sensors placed in the first layers (about 20 cm from the mat) have been clearly water saturated. A slow decrease in suction in transducers W17 and W20 started in September, which indicates that wetting has reached 40 cm from the mats. These measurements indicate that most 30/70 sections are water saturated at the perpendicular distance 20 cm from the mats and that an increased wetting has reached 40 cm in most spots but not to the centre of the backfill sections 60 cm from the mats. It is concluded that the saturation needs to continue at least for another year (2001).

4.5 Canister Retrieval Test

4.5.1 Background

SKB's strategy for the disposal of canisters with the spent nuclear fuel is based on an initial emplacement of about 10% of the number of canisters followed by an evaluation of the result before any decision is made on how to proceed. One outcome can be that the result is not accepted and that the canisters have to be recovered. In such case some, if not all, canisters can be surrounded by a saturated and swollen buffer, which holds the canister in such a grip that the canister can not just be pulled up. First the bentonite grip has to be released, for which two alternative principles can be applied; remove or shrink the bentonite. Then the canister is free to be lifted up to the tunnel and placed in a radiation shield. A concern is any type of radioactive contamination that the bentonite has been exposed to.

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. The test is separated into two phases; Design and Set-up, and the actual Retrieval Test.

4.5.2 Objectives

The overall aim of the Canister Retrieval Test (CRT) 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. In order to provide the test conditions necessary for actual retrieval tests the test set-up has to achieve the following objectives:

- 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 on of these deposition holes has been used for implementation of the CRT.
- 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.

4.5.3 Experimental concept

The deposition tunnel for the experiment is located on the 420 meter level in the extension of the D-tunnel, and is excavated by conventional drill and blast. The tunnel is 6 meters wide and as well, 6 meters high, and the centre distance between the two deposition holes is 6 meters, which is in agreement with the distance considered for the deep repository. In the Canister Retrieval Test, however, the temperature influence from surrounding canisters is less than in the deep repository, which has the effect that a higher thermal power is needed in the canister in order to obtain a temperature of about 90°C on the surface of the canisters.

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with full diameter, 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 one 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.

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.

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 are 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.

4.5.4 Results

Test of Deposition Process

The test of the deposition process was carried out from March 2000 throughout June 2000 prior to the installaton of the Canister Retrieval Test. The equipment used for the deposition process were tested and adjusted accordingly. The process of placing the buffer was practised, using concrete blocks and rings, and also deposition of the canister. The ability to maintain a levelled relative humidity in the air in order to avoid destruction of the bentonite was also tested. Processed air was ventilating the deposition hole where a bentonite block was placed in the bottom and loaded with a weight equivalent to a full column of bentonite buffer.

The main results from the Test of the Deposition Process were:

- the process of depositing buffer and canister could be adopted after minor adjustments concerning the method of placing the blocks and rings,
- the ability to sustain an acceptable climate for the bentonite was not satisfactory since leakage water from the borehole-wall could be transported along cables etc.

The borehole used for the Canister Retrieval Test is relatively dry and will therefore not be subjected to this problem. The problem with leakage water in the borehole will be addressed in a completing test after installation of the Canister Retrieval Test.

Canister Retrieval Test

Preparations for deposition of bentonite buffer and canister have been made from January 2000 throughout August 2000. Included in the preparations are:

- casting of concrete foundation on the hole bottom,
- installation of thermocouples in rock,
- drilling of holes for rock anchoring of retaining plug,
- grouting of rock anchors,
- cutting of grooves for cables,
- mounting of filter mats for artificial watering,
- installation of cone-shaped steel mould for the retaining plug,
- installation of climate control system.

Figure 4-15 shows the deposition hole prepared with filter mats, ventilation tubes, steel mould, cables from instruments and rock anchors at a stage where the buffer is partly deposited.

Deposition of the bentonite buffer, including buffer instrumentation, started September the 14th, 2000. The canister was transported from the manufacturer, Kockums in Malmö, to the Äspö laboratory and reloaded for further transportation underground to the test site. The canister was placed in the deposition hole at the 22nd of September. A test of the canister heaters revealed malfunction of a number of heaters. Too short cables had damaged the contacts during mounting of the canister lid. The canister was sent back to the workshop at Kockums for repairs and subsequently returned to Äspö two weeks later. The installation continued with mounting of heater cables and protective outer lid on the canister. The last bentonite blocks were placed on top of the canister and pellets were filled in the slot between the borehole wall and the blocks. The voids in the slot

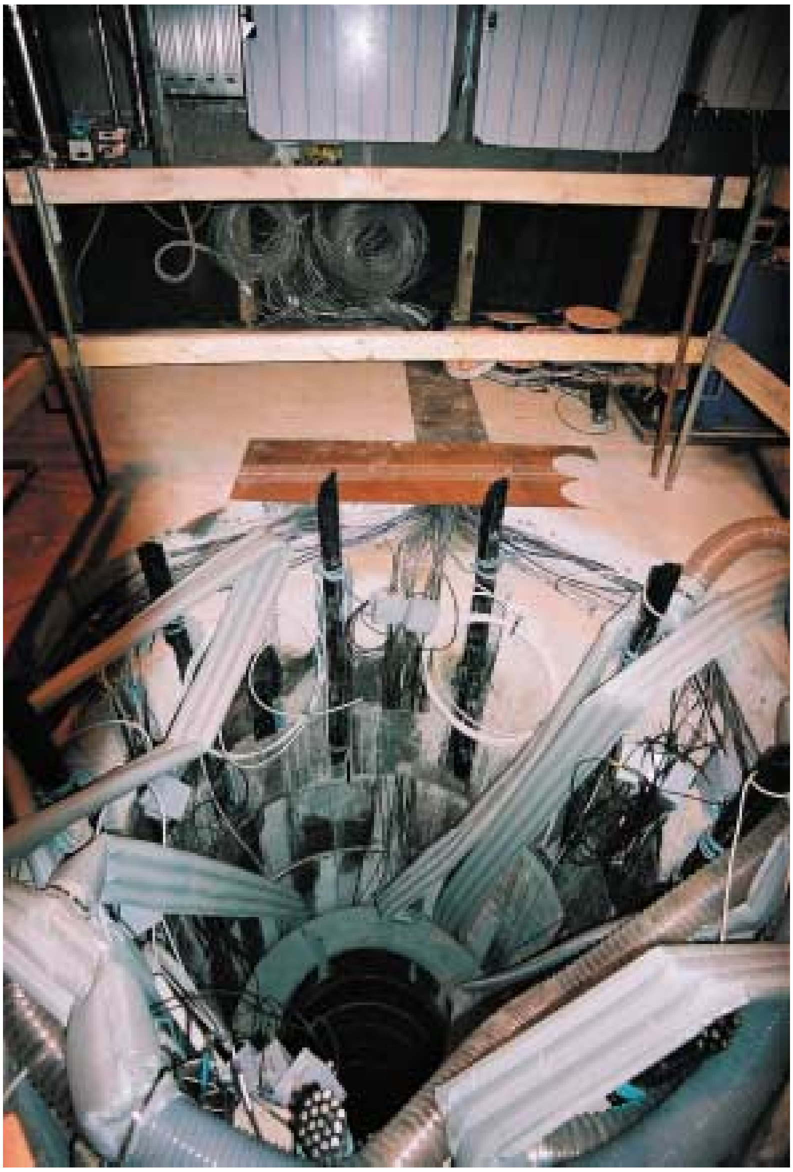


Figure 4-15. *Deposition hole during installation of buffer.*

filled with bentonite pellets were filled with water in order to provide as much water into the depositon hole as possible. Water filling was done with hoses starting from the hole bottom and pulled back in the same pace as the rising water table. The heavily reinforced concrete plug was cast immediately after water filling. A pull of the concrete plug was planned to make sure that it was not stuck in the cone-shaped mould.

The intention with a loose plug was to measure the initial vertical displacement caused by swelling bentonite. However, the pull was not performed since the plug had already moved during the time for hardening. This was an unexpected quick expansion of the bentonite. The explanation is most likely that surfaces between the blocks had been exposed to water, which was not accounted for in the predictive modelling.

The steel-plate that constitutes an integrated part of the plug was put in place and three of the nine rock anchors were subsequently pre-tensioned to fixate the system. The low pre-tension level and the elasticity of the anchors still allow vertical displacement of the plug. After the planned plug displacements had occurred the plug was fixed by distributing the force to all nine anchors and increase the pre-tensioning to a balanced level.

The heaters were turned on October the 26th at a constant effect of 1700 W. The effect will be increased to 2600 W when the temperature has reached a certain degree after approximately three months.

Instruments installed in the test have been activated and connected to the data acquisition system as the deposition went on.

Canister Retrieval Test – Measuring

A number of parameters are measured during the test to provide a basis for modelling purposes. All measurements cannot be accounted for in the annual report at this stage. The actual measurements made on-line are presented in Table 4-3.

Table 4-3. Measurements during Canister Retrieval Test.

Type of measurement
Temperature (°C) inside canister.
Temperature (°C) on canister surface.
Temperature (°C) in the buffer.
Temperature (°C) in the rock.
Rock stresses (Pa).
Total pressure (Pa) in buffer.
Pore pressure (Pa) in buffer.
Relative humidity (%) in buffer pores.
Strain (µm/m) in canister.
Heater effect (W).
Artificial watering volume (l).
Artificial watering pressure (Pa).
Vertical displacement of plug (mm).
Forces in rock anchors (kN).

4.6 Long term test of buffer material

4.6.1 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 minimize 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 alteration 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.

4.6.2 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 summarized 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 realization of the full scale test series with respect to clay preparation, instrumentation, data handling and evaluation.

4.6.3 Experimental concept

The test series (Table 4-4) concern realistic repository conditions except for the scale and the controlled adverse conditions in three tests. The testing principle for all planned tests is to emplace "parcels" containing heater, central tube, precompacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m (Figure 4-16).

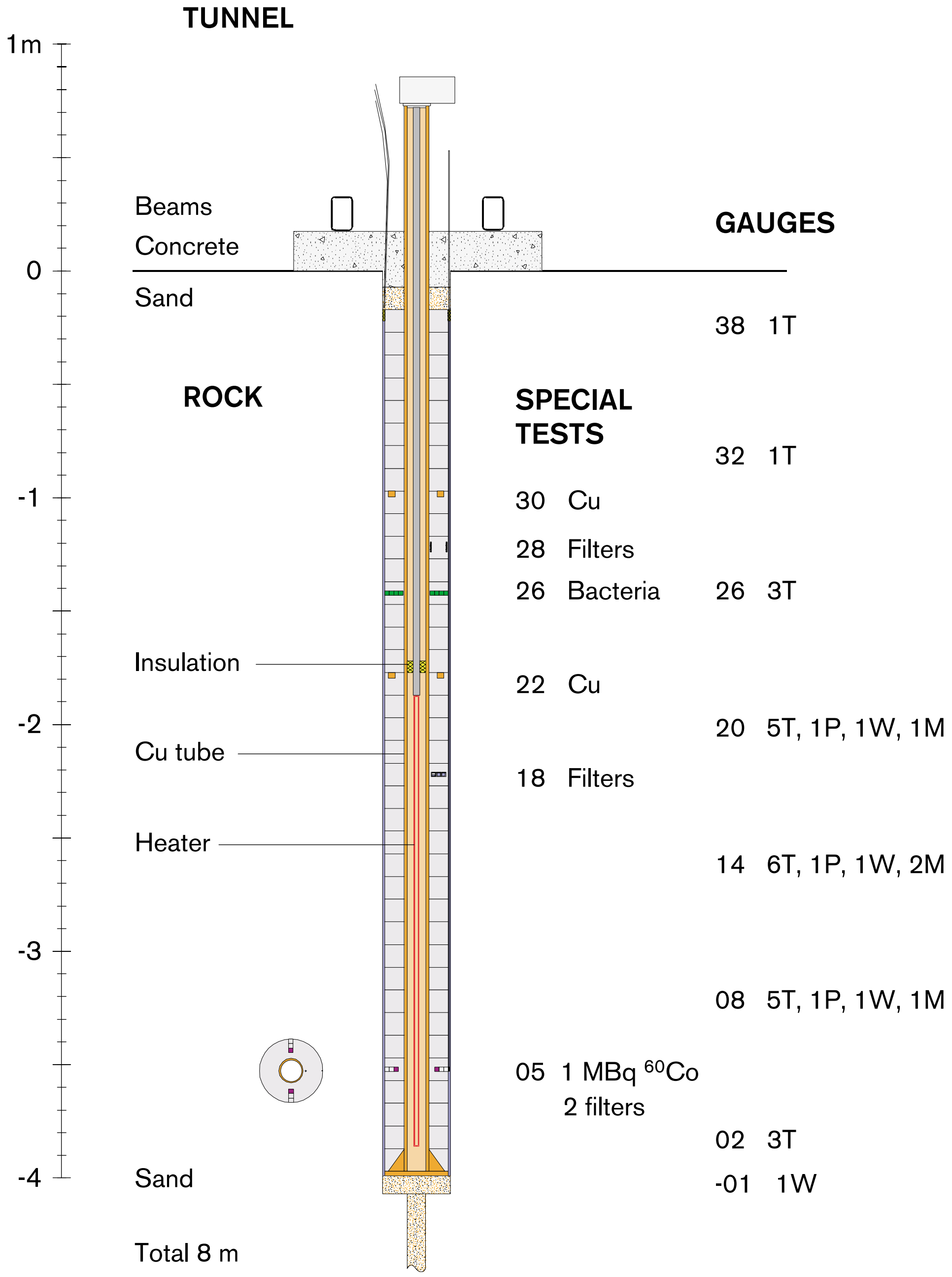


Figure 4-16. *Cross-section view of an S-type parcel. The first figures in column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.*

Table 4-4. Lay out of the Long Term 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
T = temperature
pH = high pH from cement
S = standard conditions
[K^+] = potassium concentration
am = accessory minerals added

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.

Temperature, total pressure, water pressure and water content, are measured during the heating period. 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.

4.6.4 Results

The one year pilot tests A1 and S1 have been completed and reported /SKB, 2000b/.

The 4 long term test parcels (Figure 4-16) and the additional 1-year parcel are installed in the G-tunnel, supplied with ground-water and heated to full test temperature. 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. Figure 4-17 shows the temperature distribution and evolution over the year at the warmest level of the A2 parcel, and Figure 4-18 shows the total and water pressure up build in the same clay volume.

4.6.5 Planned work

The physical properties of the 5 installed parcels will be closely followed up during the year. Minor laboratory work concerning development of test and analyse technique will be made. Planning for the termination of the A0-parcel will be started in May, and the drilling for the uplift operation is planned to start in October 2001. The various laboratory analyses of parcel material, tracer distribution, pore water and copper plates will thereafter start as soon as possible.

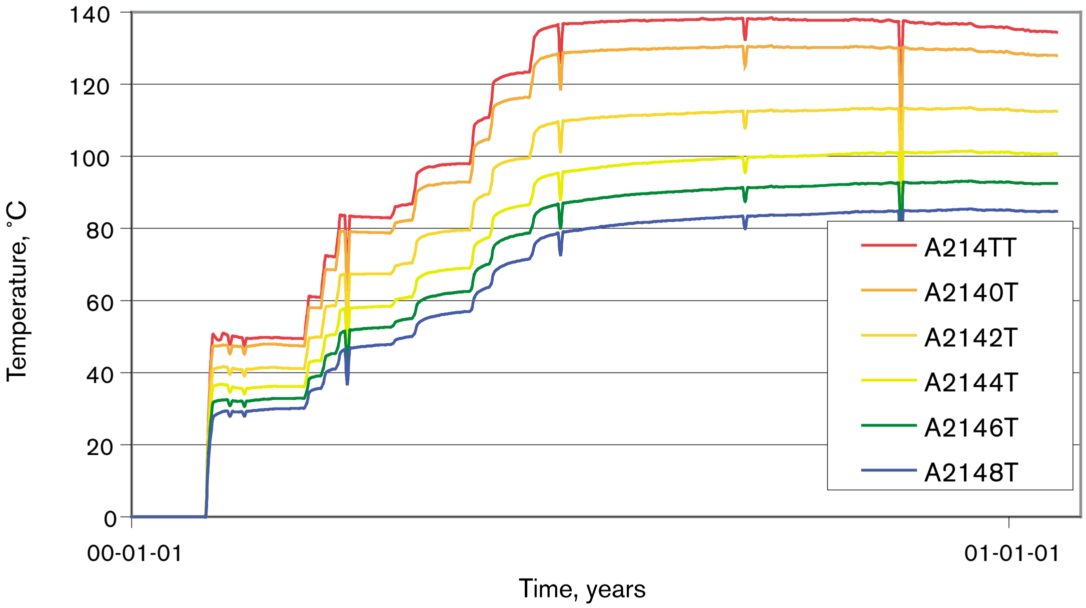


Figure 4-17. Temperature evolution in six radial distributed thermocouples in the warmest level of the A2 parcel. Uppermost curve represent the copper tube temperature, and the lowest the curve represents the temperature close to the rock.

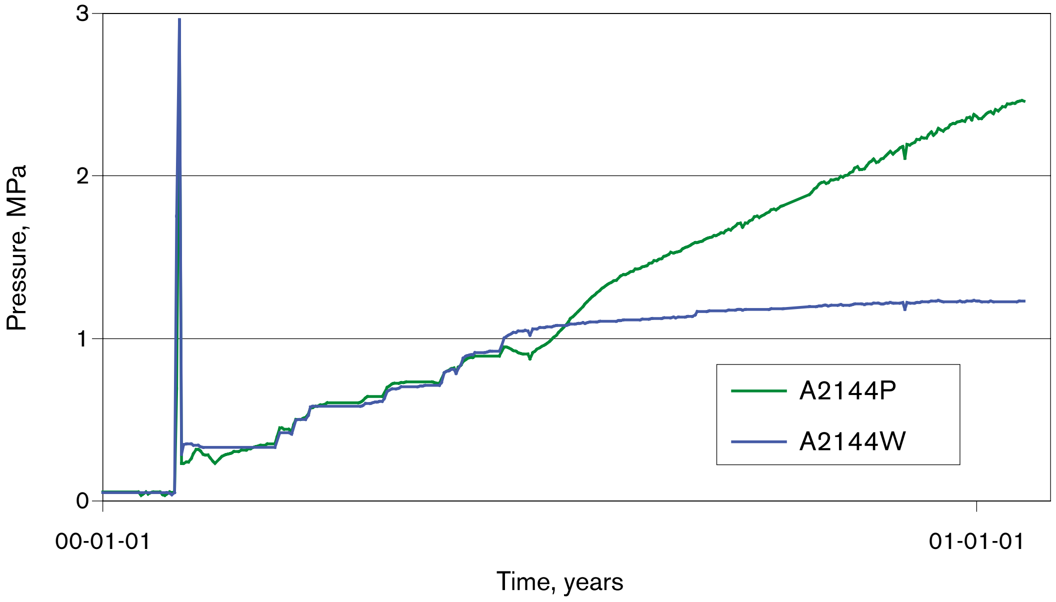


Figure 4-18. Pressure evolution in the warmest level of the A2 parcel.Upper curve represents the total pressure and the lower curve represents the water pressure. The latter has stabilised on the same value as the surrounding ground water pressure.

5 Äspö facility operation

5.1 Plant operation

Introduction

The operation of the facility has worked smoothly. A couple of new projects concerning safety, security and reliability have been initiated started and completed. These projects are described below.

Surface activities

The mainland electrical feed has been replaced with a direct feed from the OKG nuclear plant to the Äspö Research village. The previous variations in the power supply that effected the operational reliability have disappeared. The Äspö HRL now has two independent and stabile power lines. It has also been decided to keep the old mainland feed as a spare. An agreement with one electrical company has been signed to insure that the spare feed is maintained and that present and future demand of electric power is supplied.

As activities at the laboratory has increased the need for parking space has become urgentand a new parking area was built. The facilities now has an additional parking lot with room for 32 cars and 2 busses. In the spring the new area is to be surrounded with lawns in order to blend in to the environment.

Reinforcement and widening of the road to Äspö has been carried out. The refurbishing of the road is to be completed with a coating of tarmac in the spring or summer of 2001.

Underground activities

An extensive rock reinforcement programme is in progress as a result of the rock inspection in 1999. The project is expected to be completed the beginning of February 2001. At present 1 December 2001 shotcreating, bolting and mounting of mesh is carried out on the 450 m level.

A facility operation monitoring system (ALFA) has been installed, tested and approved. The system facilitates the operation considerably and gives valuable information for maintenance. Knowledge of running hours for pumps, ventilation and energy consumption will also enable optimisation of the different systems.

The project for hands-free registration when going underground has been resumed. The project has been initiated with a study in order to determine the need, technical request and possible deliverer. As the study was completed a request for offers where sent out to possible system deliverers. The offers are to be completed and returned by the end of January 2001.

A fire risk analysis has shown that improved fire safety underground is required. A project based on suggestions in the analysis has been started to improve this and the work has been initiated regard installation of traffic lights in a narrow high-risk part of the tunnel. Project will continue with additional fire detection system on the 420 m level and with voice alarm at strategic places in the underground facility.

Replacement of corroded light equipment in the deeper half of the tunnel, 220–450 m level, has started and is estimated to the completion in April 2001.

One extra mobile rescue chamber has been acquired and placed in the 420 m level.

5.2 Information and public relations

Background

The main goal of the Information group is to create public acceptance for SKB in co-operation with other departments at SKB. This is achieved by presenting information about SKB, the Äspö HRL and the SKB siting programme on surface and underground.

New Results

During the year 2000, 12 760 persons visited the Äspö HRL (12 211 persons during year 1999). Of these came 6 670 persons from the six muncipals where SKB performed feasibility studies.

The groups have represented the general public, teachers, students, politicians, journalists and visitors from foreign countries.

The total amount of visits to the SKB facilities in Oscarshamn, Äspö HRL, CLAB and the Canister Laboratory, is 19 289 during the hole year. Visits have been administrated from the information group at Äspö

Urberg 500

The new Entrance Building U500 was ready in the beginning of the year.

The official inauguration of "Urberg500" took place on March 9.

On June 19th Urberg 500 summer tours opened to the general public. It is a two hour visit starting with information followed by a guided bus tour down in the Äspö tunnel. 1700 persons participated in the tours.

Special Events

An annual event in May is "The Äspö Day". This year it took place on the 7th and 550 persons from the neighbourhood visited Äspö.

Special projects

- A new booking system/central together with OKG is planned to be ready for use during the first part of 2001.
- A safety video that is a part of the safety instructions to our visitors.
- A new visitor's site at Äspö for information on "The Drilling and Borehole investigations".

5.3 Data management and data systems

5.3.1 Background

The regulatory authorities are following SKB's siting work. Before each new stage, they *examine and review the available data*. A repository will never be allowed to be built and taken into service unless the authorities are convinced that the safety requirements are met. Hence, SKB is conducting *general studies* of the entire country and *feasibility studies* in 5–10 municipalities. *Site investigations* will then be conducted on a couple of specific sites. With the result of the studies as supporting material, SKB will then apply for permission to carry out *detailed characterisation* of one of the sites. The licence application for detailed characterisation will include a *safety assessment* and the results will be reviewed under the Act on Nuclear Activities and the Act concerning the Management of Natural Resources by the regulatory authorities, the municipality and the Government.

Management of investigation data is a highly demanding and critical task in the presented licensing process. The safety assessment must be based on correct and relevant data sets. Hence, the data management routines need to be focused on the following aspects in a long-term perspective:

- traceability,
- accessibility,
- data security and
- efficiency.

A high quality baseline for the safety assessment will be established if the aspects specified above are met. The data needed in a typical safety assessment have been reported in Andersson et al /1998/. Figure 5-1 and Figure 5-2 illustrates the need and input of investigation data in the safety assessment process.

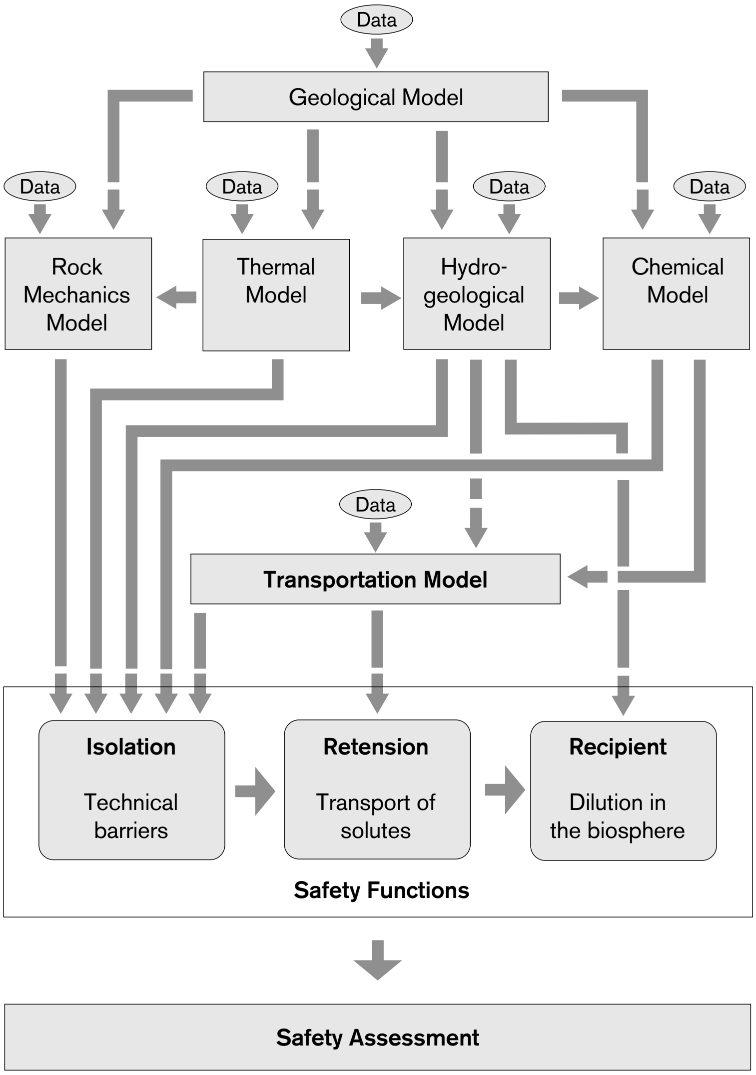


***Figure 5-1**. Schematic flow chart describing how information are transferred between different geoscientific models and how these models are used in the safety assessment to be done. The need of different types of input data are shown as balloons marked Data.*

5.3.2 Objectives

The different parts of SKB's Data Management System will be improved in conjunction with the ongoing and planned activities in SKB's siting work. This in order to fulfil the requirements expected from the regulatory authorities and the internal organisation as well.

SICADA is and will be one of SKB's most strategic database systems. The database should efficiently serve planned investigations activities at the future candidate sites as well as the experiments at Äspö HRL. The database should be user friendly and always guarantee a high degree of safety, quality and traceability.

The system need to be held modern and also adapted and improved in parallel with the development of new and more extensive investigation programs.

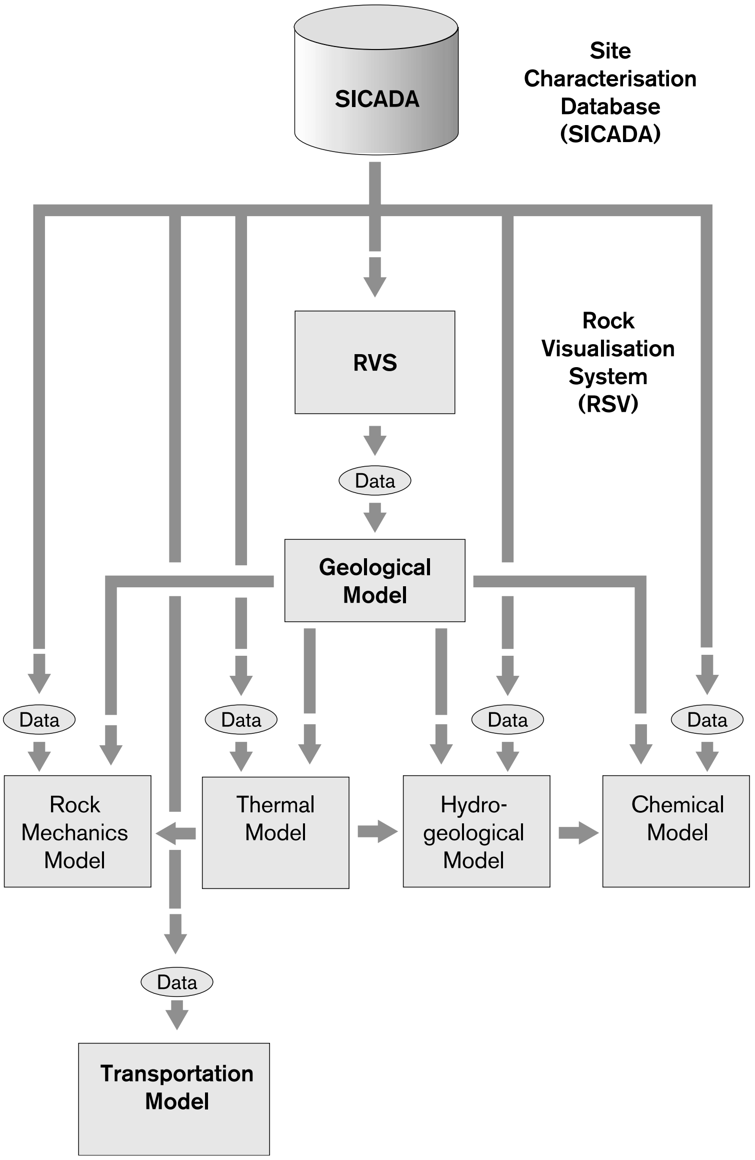


Figure 5-2. Schematic flow chart describing where from data are taken to the different geoscientific models used as a baseline fore the safety assessment to be done. The balloons in Figure 5-2 have been complemented with the origin of data. As indicated SICADA and RVS are highly important tools on the way to convince the authorities that the safety requirements are met.

5.3.3 System concept

Data model

The central data table in SICADA is the activity-history table. All data rows in this table have a unique activity identifier. This identifier uniquely connects measured data with only one activity in the activity-history table. The activity identifier is located in the first column of the table. Normally the activity identifier is hidden, but it is always present in the background and is handled automatically by the system.

Activity identifiers were introduced in order to make it possible to link an arbitrary number of investigation data tables to a certain activity. Hence, activity identifiers are present in all investigation data tables in the whole system.

All data rows in the activity-history table also have a time stamp and a user identification code to show and control when data was inserted into the table and who did the input.

Data structure

A hierarchical data structure has been inplemented in order to make it easy to find and retrieve any investigation data. The hierarchy is composed of three levels, viz:

- Science (Level 1)
- Subject (Level 2)
- Method (Level 3)

At present the data structure contains the sciences engineering, geology, geophysics, geotechnics, hydrochemistry, hydrogeology, meteorology and rock mechanics. An excerpt of the data structure is viewed in Figure 5-3.

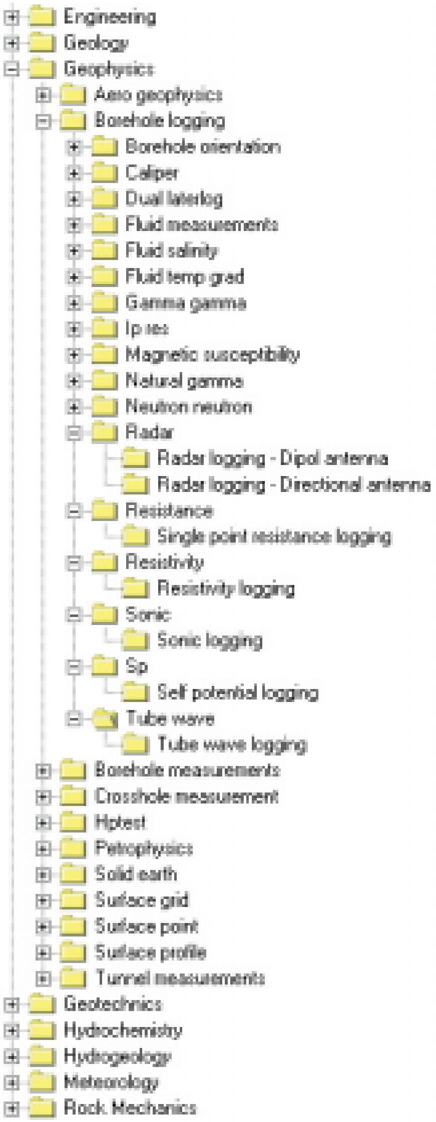


Figure 5-3. *The hierarchical data structure of the SICADA system, with all sciences shown, but only an excerpt of subjects, methods and activities. Note, in most cases there is an* ***one to one*** *association between a certain method and an activity, but in some cases a set of activities are associated with only one method.*

Every set of investigation data in SICADA has been collected from boreholes, tunnels or other objects. Simple name conventions have been set up and used for objects. For objects in the Äspö tunnel seven to nine characters are used, like for the cored borehole KA2511A. The naming of surface boreholes is somewhat different, where only five characters are used. An example is the cored borehole KAS02 and the percussion borehole HAS05. The capitals K and H is used for cored and percussion drilled holes, AS is the area code for Äspö and finally 02 is a sequence number. As an example KAS02 was drilled before KAS03 and HAS05 was drilled before HAS06. The object codes (sometimes called idcodes) and the hierarchical data structure are the key information when searching for data in the SICADA system.

All investigation data sets or parts of data sets are not possible to store in data tables in SICADA, but at least stored as *file references*. Some examples of this type of data sets are borehole radar images and geophysical profiles. The *file reference* is an optional *activity tag* available during data registration. Actually there is an on-line file archive managed by the SICADA system. This on-line archive is called *SICADA File Archive*. A registered *file reference* is actually an on-line reference to the file in the SICADA File Archive.

The *activity tag* mentioned above is only one example of one of many useful tags in the SICADA system. There are currently about 60 different tags available in the system.

Applications

The following SICADA user applications/programs are used to handle the information in the database.

SICADA/**Diary**	This application is used to *insert or update* data in the database.
SICADA/**Finder**	This application is used to *retrieve* data from the database.
SICADA/**Retriever**	This application is used to *retrieve* data from the database.
SICADA/**Project**	This application is used to *check* the progress of the data entry work for a specified project/experiment.

5.3.4 Results

The full integration of the HMS instrument database as a part of SICADA has been completed. Some new improvements have also been introduced, and the set of instrumentation data has been complemented. After integration the instrumentation database was settled.

The licensing technique for CA/Ingres II and other CA-products, has earlier caused severe problems, have been replaced by a new technique.

Major efforts have been undertaken to improve the part of the data structure used for management of information about all co-ordinate systems handled in the database. The Rock Visualisation System required the modifications implemented.

The SICADA administration organisation has been extended with a new employee, assistant database administrator, as planned. The head database administrator will now have more time to focus on other important activities e.g. implementation of GIS methodology.

5.4 Monitoring of groundwater head and flow

5.4.1 Background

The Äspö HRL operates a network for the monitoring of groundwater head, flow in the tunnel and electrical conductivity, as the core parameters. This system goes under the acronym of HMS (Hydro Monitoring System). Water levels and pressure head are collected from surface and tunnel boreholes. Additionally, the electrical conductivity of the water in some borehole sections and in the tunnel water is measured. The network includes boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen and some boreholes on the mainland at Laxemar.

The monitoring of waterlevels started in 1987 while the computerized HMS was introduced in 1992. The number of boreholes included in the network has gradually increased. The tunnel construction started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992. To date (31 December 1997) the monitoring network comprise a total of 62 boreholes most of which are equipped with inflatable packers, where the pressure is measured by means of pressure transducers. The measured data is relayed to a central computer situated at Äspö Research village through cables and radiowave transmitters. Once a year the data is transferred to SKB's site characterization 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.

The tunnel excavation began to impact on the groundwater head during the spring 1991.

5.4.2 Objectives

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

- firstly it is a necessary requirement in the scientific work to establish a baseline of the groundwater head and flow situation as part of the site characterization exercise. That is, a spatial and temporal distribution of groundwater head prevailing under natural conditions (i.e. prior to excavation),
- secondly it is indispensable to have such a baseline for the various model validation exercises which are implemented for the Construction Phase and the Operational Phase including the comparison of predicted head (prior to excavation) actual head (post excavation),
- thirdly it was conditioned by the water rights court when granting the permission to execute the construction works for the tunnel that a monitoring programme 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.

5.4.3 Results

The hydro monitoring system continued to support the different experiments undertaken at Äspö HRL. It provides basic information on the influence of the tunneldrainage on the surrounding environment by recording the evolution of head, flow and salinity of the groundwater.

Support of experiments

HMS data were put to use in different ways, in addition to complying with the water rights court it provided the means to continuously control the groundwater head in a rock volume where tracer experiments are conducted. The head distribution in the block should remain constant throughout the experiment since it forms an initial condition to the problem. Alteration in head gradients during the experiment might complicate the analysis. It is always supporting, and indeed is a necessary requirement during the rock characterization stage preceding the experiments.

As an example, it was noted through the HMS that during the blasting of the support for the plug in the tunnel for the Prototype Repository experiment that the groundwater pressure in neighbouring fractures/fracturezones did not restore to their original level after blasting. This effect warrants further studies. Se section 4.2.4.

5.5 Quality Assurance

5.5.1 Background

Quality Assurance means to ensure that activities are undertaken with due quality and high efficiency. In order to achieve this goal it is required that a smoothly running systems is in place to manage projects, personnel, purchasing, economy quality, safety and environment.

The structure of a quality assurance system is based on procedures, handbooks, instructions identification and traceability, quality audits etc. The overall guiding documents for issues relating to management, quality and environment are written as routines.

Employees and contractors related to the SKB organisation are responsible for that the works is performed in an order so it fulfils SKB's quality goals and guidelines.

5.5.2 Objectives

SKB is in progress to implement a common management system to break down all requirements from legislator, authorities, other interested parties and internal requirements of our own organisation. The aim of the project is to certify SKB according to the Environmental Management System ISO 14001 and also to the Quality Management Standard ISO 9001 before the summer of year 2001.

The SKB's Management System has been compared to the requirements from the ISO-standards. This work has resulted into actions.

5.5.3 Results

One internal audit has been executed. Actions have been taken to take care of the deviations from the ISO-standards.

Goals and actions plan to reach the environmental goals have been identified and important environmental aspects which influence the environment.

Several routines have been produced to manage quality, safety and environment to the Äspö HRL.

6 International cooperation

6.1 Current international participation in the Äspö Hard Rock Laboratory

Nine organisations from eight countries have during 2000 been participating in the Äspö Hard Rock Laboratory in addition to SKB. They are:

- Agence Nationale pour la Gestion des Dechets Radioactifs, **ANDRA**, France.
- Bundesministerium für Wirtschaft und Technologie, **BMWi**, Germany.
- Empresa Nacional de Residuos Radiactivos, **ENRESA**, Spain.
- Japan Nuclear Cycle Development Institute, **JNC**, Japan and The Central Research Institute of the Electric Power Industry, **CRIEPI**, Japan.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, **NAGRA**, Switzerland.
- United Kingdom Nirex Limited, **NIREX**, Great Britain.
- **Posiva OY**, Finland.
- **US DOE CBFO**/Sandia National Laboratories, **SANDIA**, USA.

In each case the cooperation is based on a separate agreement between SKB and the organisation in question. The cooperation with the Japanese organisations is performed under one agreement. JNC is the official representative within the cooperation. The work performed within the agreements and the contributions from the participants are described under section 6.2.

Multilateral projects are established on specific subjects within the Äspö HRL programme. These projects are governed by specific agreements under the bilateral agreements. The TRUE Block Scale Experiment (see section 3.3.2) is an example of such a project.

Specific technical groups so called Task Forces is another form of organising the international work. A Task Force on groundwater flow and solute transport in fractured rock is ongoing (see section 3.9).

A joint committee, the Äspö International Joint Committee, IJC, with members from all participating organisations, except from Japan which is represented by JNC only (see above), is responsible for the coordination 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.

6.2 Summary of work by participating organisations

6.2.1 Posiva

Introduction

The Project Agreement between SKB and POSIVA covers the co-operation in the Äspö HRL. The work within the Joint Project comprises three main areas:

- Detailed investigation methods and their application for modelling the repository sites.
- Test of models describing the barrier function of the bedrock.
- Demonstration of technology for and function of important parts of the repository system.

According to a specific agreement Posiva is participating in TRUE Block Scale (TBS) experiment together with Nirex, ANDRA, SKB, ENRESA and PNC.

The following text comprises the work done during 2000 according to the Joint Project.

Detailed investigation methods and their application for modelling the repository sites

Applicability of different investigation methods for assessment of repository sites

Posiva conducted an investigation programme in the Laxemar KLXO2 borehole by the technology used in the site characterisation programme in Finland. Details of this study are presented in the description of the Hydrochemical Stability project.

Test of models describing the barrier functions of the bedrock

Task Force on Modelling of groundwater flow and transport of solutes

Task 5: Impact of the tunnel construction on the groundwater system at Äspö – a hydrological-hydrochemical model assessment exercise

Background

Task 5 (Impact of the tunnel construction on the groundwater system at Äspö, a hydrological-hydrochemical model assessment exercise) aims at the comparison and ultimate integration of hydrochemistry and hydrogeology. The simulation of reactive transport on the aerial scale to the Äspö HRL is beyond present scope for several reasons. Therefore, the task "modelling of groundwater flow and transport of solutes" was broken down into two sub-tasks: to studies of groundwater chemistry and to hydrogeological simulations both done by VTT/Infrastructure and Environment. Task 5 is also part of the Hydrochemical Stability project.

Objectives

The groundwater chemical studies done in VTT aimed to the independent approach to the SKB's M3 method /Laaksoharju and Wallin, 1997/. The geochemical *inverse modelling calculations* attempts to take several aspects contemporaneously into account during calculations. 1) Calculations were performed using the reference water types that have been identified based on the analyses of geochemical data, 2) on the interpretations of the Quaternary history of the Äspö HRL (Figure 6-1), and 3) the calculated geochemical

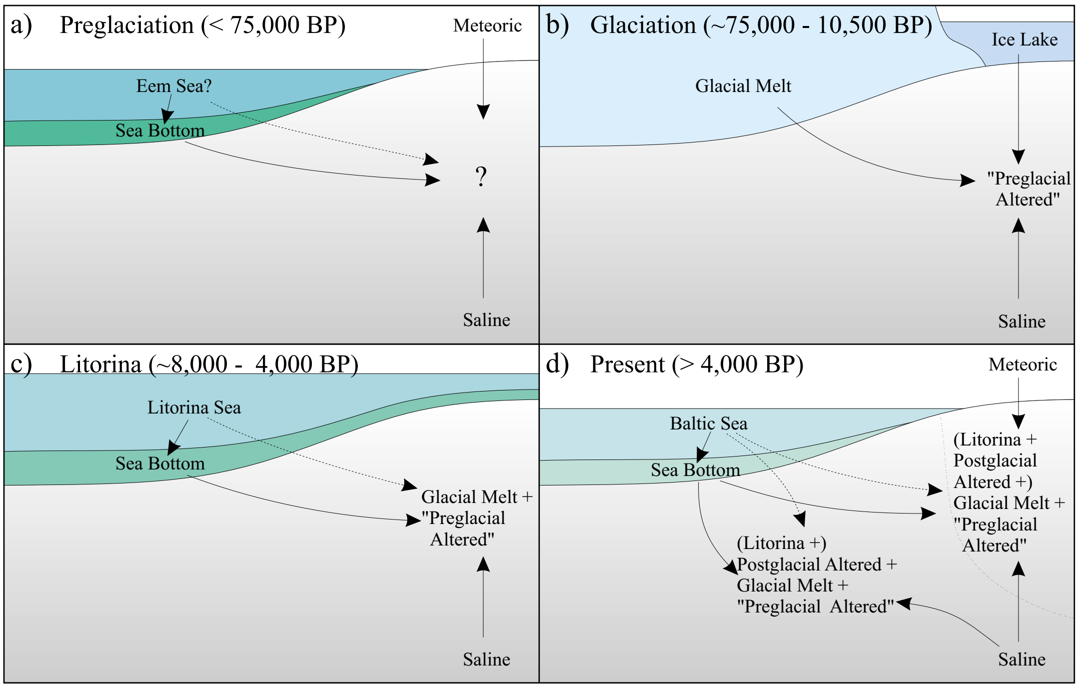


Figure 6-1. *Quaternary history of the Äspö area, based on analyses of geochemical data and interpretations of the Quaternary history of the Fennoscandian Shield /e.g. Laaksoharju and Wallin, 1997/. Only periods considered significant for groundwater evolution at the Äspö site are presented.*

mole-transfers are assumed to conform the geochemical steady-state conditions. Important results of the inverse modelling calculations are the mixing fractions.

In the hydrological simulations the mixing fractions of the reference water-types can be transported like conservative parameters. The initial geochemical boundaries for hydrological simulations are given as mixing fractions. In the hydrological simulations the mixing fractions are transported as a function of time, and the evolution of mixing portions in the predefined control is monitored. Detailed performance measures are used for the presentation of the results.

Experimental concept

The flow model was constructed by including the hydrologic connections recognised during the tunnel construction. The observed properties of water and bedrock were included in the simulation model. The groundwater table applied over the Äspö island was replaced by a flow rate boundary condition in the first updating of the tunnel. The hydraulic data gained from boreholes was utilised to confirm the residual pressure and flow rate boundary conditions in the tunnel and the shaft(s).

In essence, the simultaneous modelling of flow and transport is a coupled process. The initial salinity or chloride boundary was fixed in accordance with the observations of the groundwater composition. The FEFTRA code, which is based on the porous medium concept and the finite element method, was used to solve both the coupled equations of residual pressure and concentration and the transport equations of the different water types.

The simulation time steps covered the period from the natural conditions until the completion of the tunnel and the shafts. The dual porosity transport model was applied to the equations of the different groundwater types, which were solved using the previously simulated residual pressure and concentration fields. The initial concentration boundary condition for the transport equations of the different water types was given in the basis of the M3 modelling and the inverse modelling.

The geochemical inverse modelling calculations aims at solving step by step reference water mixing fractions in groundwater samples collected from the Äspö HRL. Simultaneously the net geochemical reactions required for reaching the sample composition are solved. The approach implements the inverse-modelling method (PHREEQC-2) and calculations are carried out both samples taken before the excavation of the HRL tunnels (undisturbed conditions) and samples taken during and after excavations (disturbed conditions).

Results

The POSIVA's contribution to the Task 5 resulted three reports, one on the geochemical inverse modelling and two on the hydrological simulations, to be published in 2001. The whole hydrological simulation process was done twice because there were two sets of geochemical modelling results available for the simulations. The M3 based geochemical results were delivered by the Task 5 organisation but the inverse modelling based geochemical results were calculated in the VTT.

As regards the M3 based simulated mixing ratios in the control points, the future condition of the brine water seems steady, except in the prediction section (tunnel length > 3000 m), where it is mildly increasing. The glacial water decreases, because it is a relic component in the present-day groundwater conditions. The meteoric water generally increases. The overall future condition of the Baltic water seems quite steady. These results are fairly well in line with the M3 modelling. The tunnel construction caused the upconing of the brine water, the decrease of the relic glacial water and the increase of the mixing ratios of the meteoric and Baltic waters in the tunnel area. This piece of work showed the essential role of the dispersion lengths as regards to the calculated mixing ratios at the control points. Also, the infiltration from the sea had to be restricted.

In the geochemical inverse modelling the calculation results for the undisturbed conditions form the basis for disturbed sample calculations. Furthermore, the detected depth distributions of mixing fractions in undisturbed samples form geochemical boundaries necessary in hydrological simulations. An example of results of disturbed condition calculations is given in Figure 6-2 that illustrates how mixing fractions evolve in time in a control point, and how large CaX_2 mole-transfers has to be taken into account as a function of fresh Baltic Sea fraction intruding into a control point.

On the whole, the inverse modelling based simulations give good or fair results at shallow depths compared to the estimated mixing fraction results. Adjusting the surface boundary conditions and the transmissivities suitably usually solved the shallow problems. At depth, the simulations exhibit either a systematically growing difference to the geochemically estimated values, or hint to an exaggerated stiffness of the hydrological model. These difficulties raised three principal questions: "are the hydrological/structural properties of the fracture zones correctly estimated at depth, are the structural relations between the fracture zones correctly defined, and is the open tunnel effect taken correctly into account in the hydrological model?"

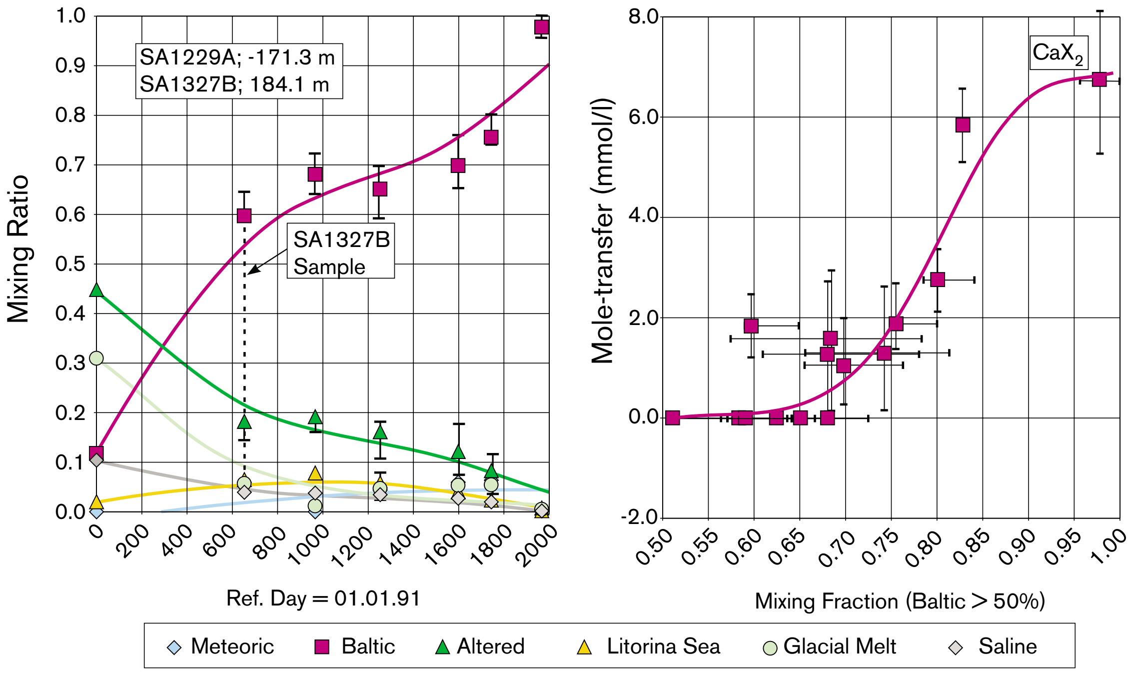


Figure 6-2. *Reference water-type mixing fractions in the control points SA1229A and SA1327B as a function of time, and CaX_2 mole-transfer as a function of the fresh Baltic Sea fraction. Cumulative maximum errors in mixing fractions and maximum errors related to mole-transfers are shown with error bars. Drawn regressions are visual approximations.*

Hydrochemical stability project

Background

Posiva and SKB initiated in 1997 a joint project with the aim to investigate the hydrochemical stability of deep groundwater in crystalline bedrock. This project has been carried out within the Äspö agreement between SKB and Posiva. It also covers the technical parts of the participation in the modelling Task 5 (within the framework of the Äspö Task Force for modelling of groundwater flow and transport of solutes) and re-sampling and analysis of groundwater from KLX02. The project is in a final reporting stage. Results of Task 5 are explained above and results of flow measurements of KLX02 with Posiva flow log are shown below.

Fieldwork in borehole KLX02 at Laxemar

The aim of the joint SKB/POSIVA measurements of the deep borehole KLX02 at Laxemar was to demonstrate Posiva's new flow measurement and sampling techniques and to compare the results with earlier measurements from this borehole. The overall goal was to increase the information from deep saline groundwater in Sweden and Finland. The equipment used were Posiva Flow Log (Figure 6-3) for hydrogeological determination of the flow situation including also the EC-electrode (to be used for the estimation of TDS), and the PAVE equipment for groundwater sampling (done during 1999).

Figure 6-3. Posiva Flow Log was used in flow measurements in borehole KLX02 at Laxemar.

During the year 2000 two campaigns of flow measurement was carried out in the borehole KLX02. The objective of the measurements of the first campaign (January – February 2000) was to determine hydraulic conditions in the borehole. The main feature discovered was that the flow direction in the measured depth range of 200–1200 m was from the borehole into the bedrock when the borehole was in natural state (without pumping). Pumping reversed the flow direction. There was not any flow detected under 1200 m depth. Hydraulic head and hydraulic conductivity was interpreted from the measured flow and fresh water head values.

1. The second flow measurement campaign was carried out in borehole KLX02 in May-June 2000. A methodology test of the Posiva flowmeter was performed as a part of the Joint Project between Posiva and SKB. The second campaign had two main objectives:
2. To evaluate possibilities to obtain transmissivities of individual fractures from the results of the flow measurements.
3. To perform detailed flow logging with EC (electric conductivity of groundwater) measurement to obtain flow rates of fractures and fracture specific EC of groundwater coming from chosen fractures.

For the first objective, the borehole was pumped with several pumping rates (drawdowns). The results showed reversed flow directions without pumping and with pumping and flow rate increased with increasing pumping rate, see Figure 6-4. The preliminary results for the first objective have been delivered to SKB. The benefits as well as the limitations of the method will be analysed in a report which will be published in 2001.

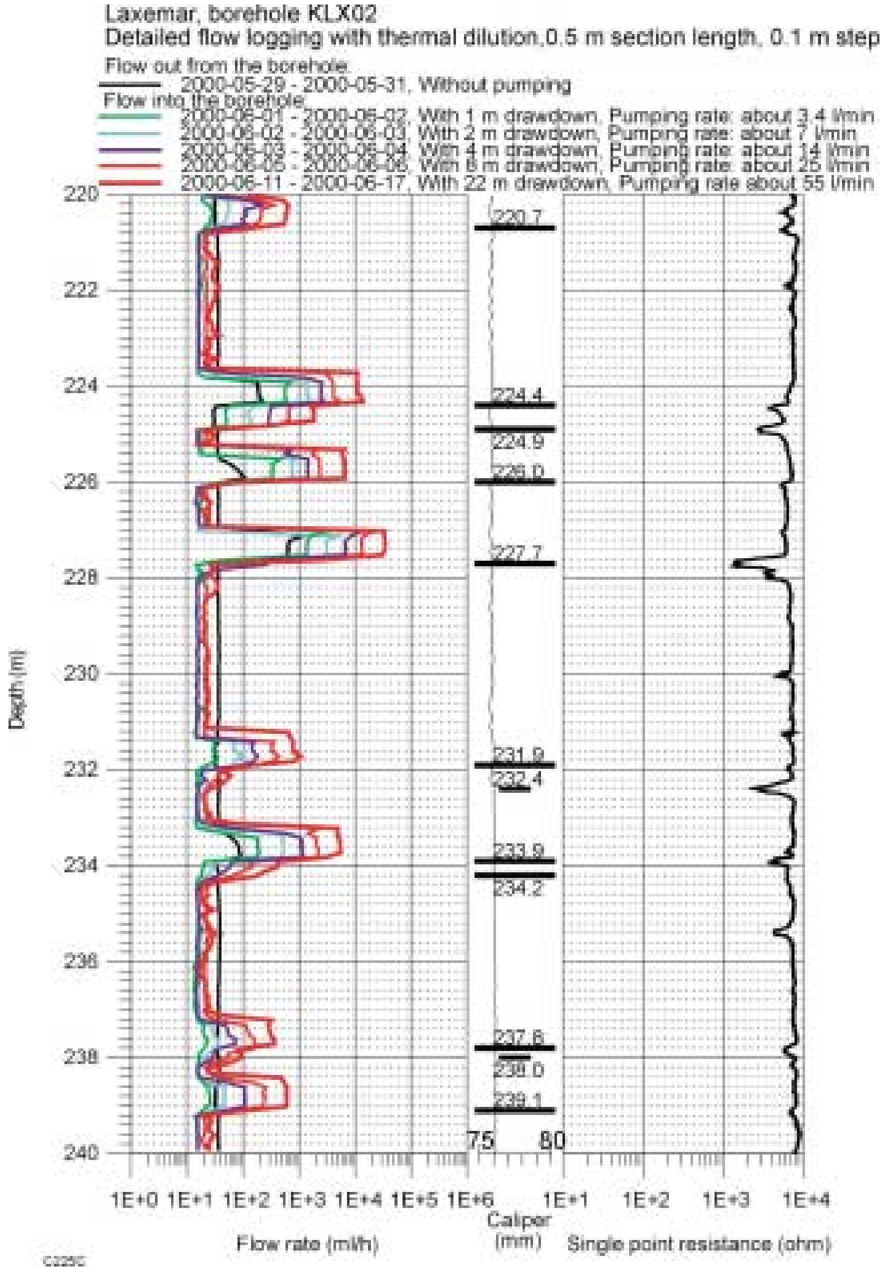


Figure 6-4. *An example of the results of the methodology test, detailed flow logging with several drawdowns.*

Microthermometry and LA-ICP MS investigation in connection with Äspö Matrix Fluid Experiment

Background

The fluid inclusions (FI), being a conceivable reservoir of salinity in crystalline rocks, contribute essential geochemical evidence for the main objectives of the matrix fluid project, which are: 1) to determine the origin and age of the matrix fluids 2) to establish whether present in- or out-diffusion processes from nearby fractures/fissures have influenced the composition of the matrix fluids and vise versa and 3) to derive a range of groundwater compositions as suitable input for near-field model calculations

The present investigation aims to 1) to find out the FI appearance in Äspö diorite 2) to distinguish the chemical characteristics of the fluid inclusions and 3) to evaluate the value of Laser Ablation ICP MS methods in determination of FI compositions. Moreover the results of this work are weighted against the analytical data given by Raman spectrometer (analyses carried out by Dr. Sten Lindblom in Stockholm University). Double polished thin sections, 200 µm in thickness, were prepared from seven rock samples at Stockholm University. All the samples were selected from drill core sample KF0051A01. The analytical methods consist of petrographic microscope, microthermometry (Reynolds Fluid Inc.) and Laser Ablation ICP-MS equipment (Cetah-Perkin Elemers 6000).

Results

The fluid inclusions in coarse-grained quartz and in plebby quartz of Äspö diorite bear record of repeated fracturing, recrystallization and refracturing episodes. Three types of inclusions were found; vapour, vapour-liquid and liquid. Moreover in one sample a vapour-liquid-solid fluid inclusion was detected. The vapour phase in vapour-liquid fluid inclusions is CO_2 and it occupies most generally between 10 and 20% of the total volume of the inclusion. The inclusions measure from 5 to 20 µm in length. Most of the inclusions occur in quartz, only few of them were detected in apatite and in sphene. The FI's appear as 1) small clusters in crystals, 2) isolated and 3) related to intragranular fractures. The type 3 is the most common and it carries the majority of the FI's. The fluid inclusion trails in these fractures are aligned in several cross cutting directions, which tend to continue directly though the section

The microthermometric analyses (Figure 6-5) indicate low to moderate salinity for the aqueous – carbonic fluids. The melting temperatures determined range in general from –4°C to –17°C, which suggests 5–22 wt % $NaCl_e$. The homogenization temperatures lay within range of 89,6–190°C in most of the determinations, although higher values, up to 271,2°C, have been recorded.

The La-ICP-MS study indicates the dominating cations in FI's to be sodium, calcium and magnesium. Furthermore several of the laser transverses, which were focused to the grain boundary inclusions, reveal elevated concentration of barium.

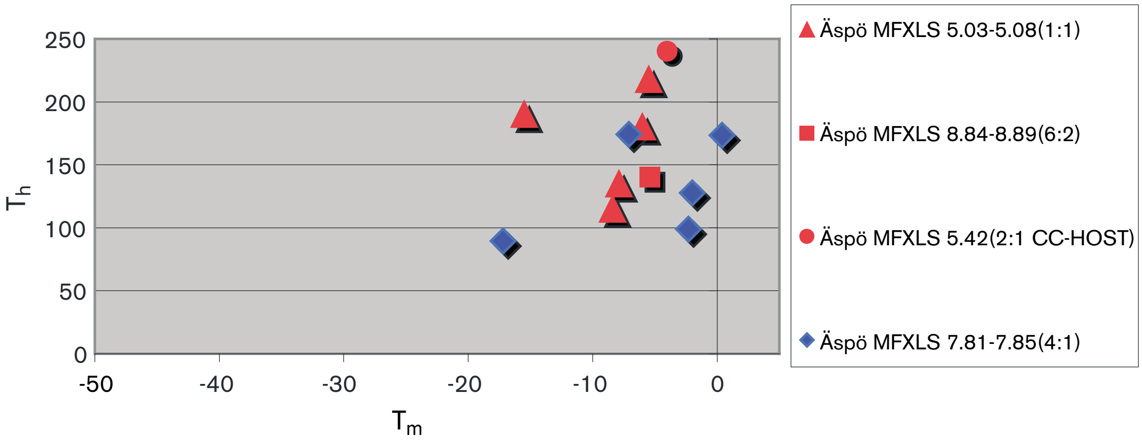


Figure 6-5. *Microthermetry results for quartz-hosted FI's in Äspö diorite samples 5.03–5.08 m, 5.42 m and 8.84–8.89 m, drill core KF0051A01.*

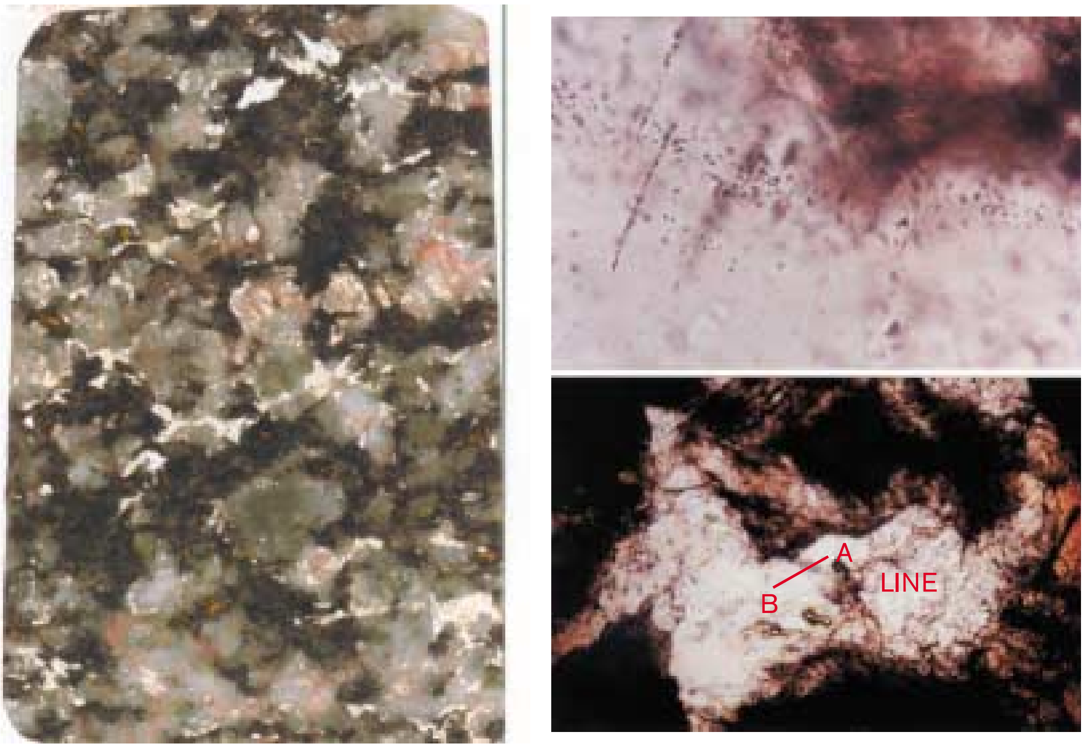


Figure 6-6. A scan of double polished thin section (above) from sample KF0051A01 – 5.03–5.08 m. Quartz stands out as white grains. Yellow arrow points the area enlarged in the photos on the right. Photo on the right shows a trail of fluid inclusions in the quarz host. The location of LA-ICP MS profile A'–B' is marked. The profile A'–B' (figure on the rigth) across a quartz grain bursts in a middle of the transverse one sodium rich fluid inclusion.

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

Long Term Test of Buffer Material (LOT)

Background

Test "parcels" containing heater, central tube, clay buffer and instruments are placed in boreholes with a diameter of 300 mm and a depth of around 4 m for different time periods. The parcel material will thereafter be examined by a general, well-defined set of tests and analyses in order to provide data for the different aims. Posiva's task in the LOT project is to study porewater chemistry in bentonite. The task will be carried out at VTT Chemical Technology. Excavation of the next parcel (A0) is scheduled for the second half of the year 2001.

Objectives

The aim of the work carried out by VTT Chemical technology is to obtain data of the chemical conditions to be developed in bentonite considering the effect of the temperature, additives and rock fractures. The study gives information about the chemical processes occurring in bentonite, but also supports the other planned studies in respect of the chemical conditions.

Results

The development work of the measurement and analytical methods for bentonite and bentonite porewater has been completed and reported. The methods were tested with artificial samples considering the small sample size of 1 to 2 ml, which was assumed to be available. Most of the components of interest can be determined from a squeezed porewater sample of about 1.5 ml by diluting the sample. ICP-AES appeared to be a suitable routine method for Na^+, K^+ Ca^{2+}, Mg^{2+}, Si^{4+} and ion chromatography (IC) for Cl^- and SO_4^{2-}. Sulphide with spectrophotometric method likewise Fe^{2+} and Fe_{tot} with ferrozine method could be determined down to a level of 0.1 mg/l in the initial sample. Bicarbonate was determined by titration, the determination level being 1 mg/l in the initial sample.

The tests on pH showed that a sample of 0.15 ml was big enough for the microelectrode to give reliable values. The tests on Eh with reference porewaters, where different concentrations of S(-II) or Fe(II) were added, showed that the sample has to be closed carefully in the measurement cell to avoid oxidation or loss of H_2S. A sample of 0.3 ml is enough for the microelectrode.

A squeezing cell for porewater prepared of titanium was tested with bentonite samples and sulphide solutions. A vessel was constructed and tested for transportation of the bentonite samples to be taken from the LOT experiment.

6.2.2 ANDRA

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

The contributions of ANDRA and its contractors focused on the *Tracer Retention Understanding Experiment (TRUE) at a Block Scale (TRUE BS)* and on the *Task 5 of the Äspö Task Force on modelling* dealing with hydro-chemical modelling of the perturbations due to construction of the HRL

TRUE Block Scale Experiment

ANDRA and its contractors carried out suple efforts in the tracer tests phase of the TRUE BS Experiment:

- One concerning tracer tests strategy, field work and interpretation of results.
- One on the modelling side to help dimensioning tracer tests.

Tracer tests background (ANDRA, SOLEXPERTS, GEOSIGMA)

Tracer tests have been carried out in order to characterise a granitic block hydraulically. The conceptual model developed in the previous boreholes characterisation phases served as a base to elaborate the tracer tests plan. This hydro-structural model comprises almost twenty sub-vertical structures (Figure 6-7). All high transmissivity structures (10^{-7} to 10^{-5} m^2/s) are NW oriented. The mean gradient of 8% is towards the laboratory tunnel. Dilution tests carried out in various boreholes intersections of the same structure proved very different fluxes.

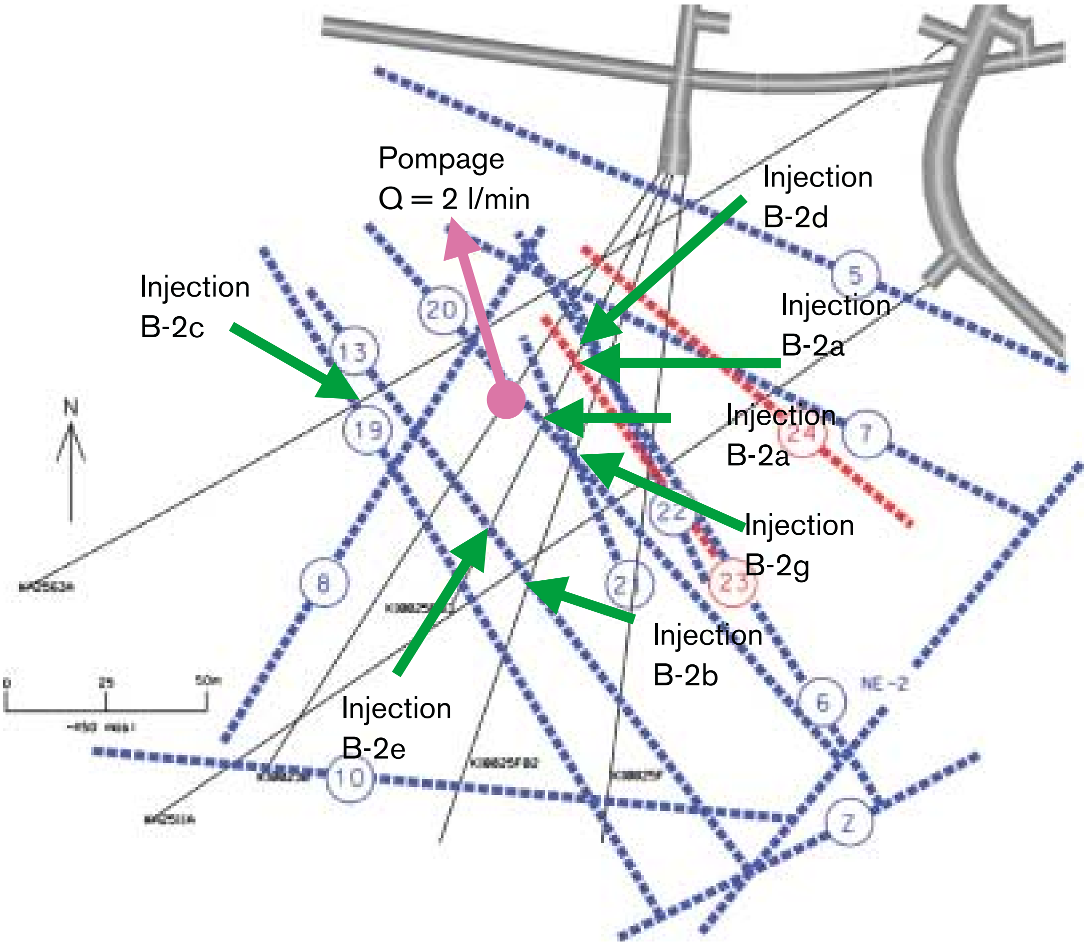


Figure 6-7. Hydro-structural model at level –450 with sinks and pumping locations.

Tracer tests objectives

The 2000 sorbing and non-sorbing tracer tests aimed at:

- Understanding and forecast transport in a given fractures set.
- Evaluating the tracer retention mechanisms (matrix diffusion, sorption).
- Finding a link between flux and transport parameters.
- Evaluating the role on transport of fracture heterogeneity and intersections.

Tracer tests plan and results

The 2000 tracer tests plan followed a step by step strategy:

(A) The first phase aimed at finding the most suitable experimental design having in mind a minimum recovery target of 80% for sorbing tracers. Two configurations proved efficient with low injection rate compared to high extraction rate (~2 l/min): dipole and radial convergence. The best sink proved to be the intersection of borehole KI0023 with structure 20.

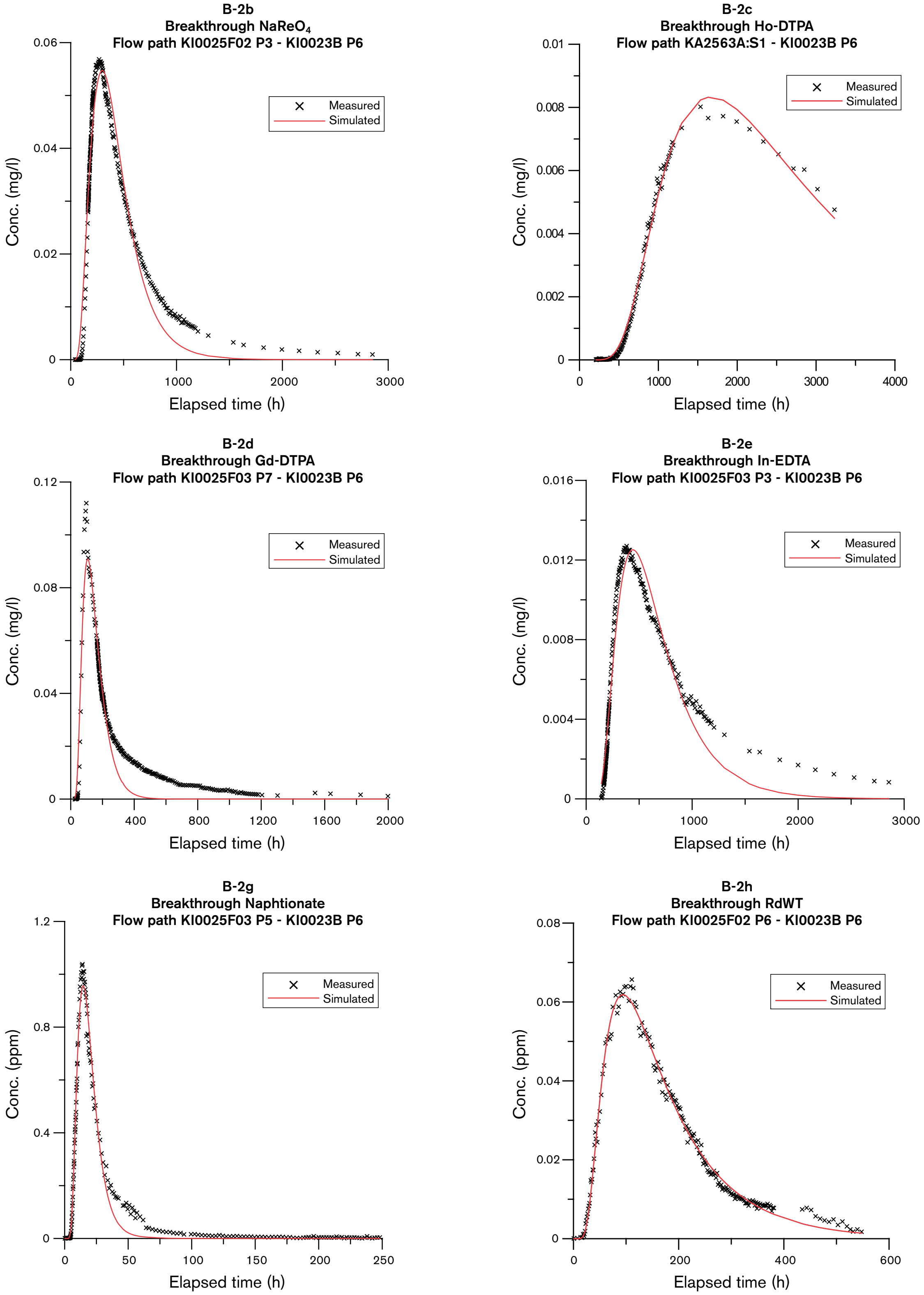


Figure 6-8. *Non-sorbing tracer concentrations (B-2b to h) in the pumped water (rate~2 l/min) at structure 20 and borehole KI0023 intersection.*

(B) During the second phase, various non-sorbing tracers (He-3, uranine, Yb-EDTA, ReO4, Ho-DTPA, Gd-DTPA, In-EDTA, naphtionate, rhodamine WT) have been injected in 7 locations of the fracture network. The tracer concentrations in the pumped water have been measured during months (Figure 6-8) to obtain a data set useful to achieve the objectives of the next step. The arrival times and the concentration curves shape differ with the injection point. Matrix diffusion seems to play a role, considering the results with a Yb-ETA, He-3 cocktail (Figure 6-9).

(C) With the third phase, cocktails of sorbing tracers with different sorption coefficients (H-3, Br-82, Na-22, Na-24, K-42, Ca-47, Sr-85, Cs-134, Re-186, Rb-86, Mn-54, Co-57) have been injected in 3 selected locations (where non-sorbing tracers recovery had been found > 80%). The retardation effect related to each tracer is well observed (Figure 6-10) and is in accordance with the knowledge acquired on a single fracture with TRUE-1. The –3/2 slope of the Log Log plot could indicate a matrix diffusion effect similar to observations made in the Swiss Grimsel Test Site. Analysis of these results are still under way.

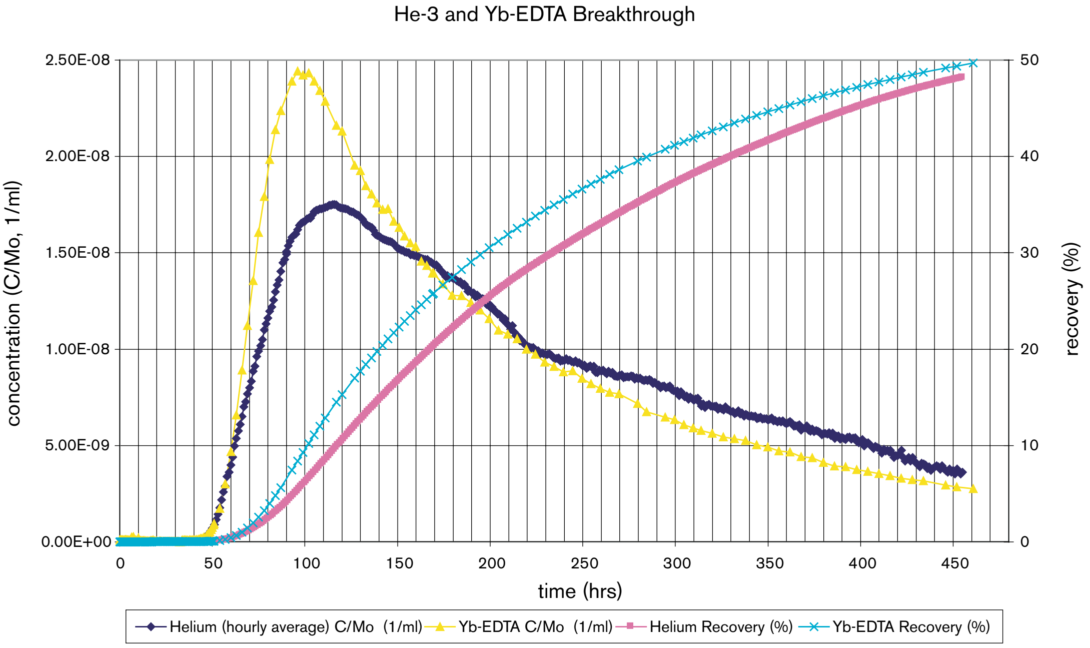


Figure 6-9. *B-2a test with He-3 and Yb-EDTA. Later arrival of He-3, smaller maximum concentration and longer tale may indicate diffusion in rock matrix or stagnant zones.*

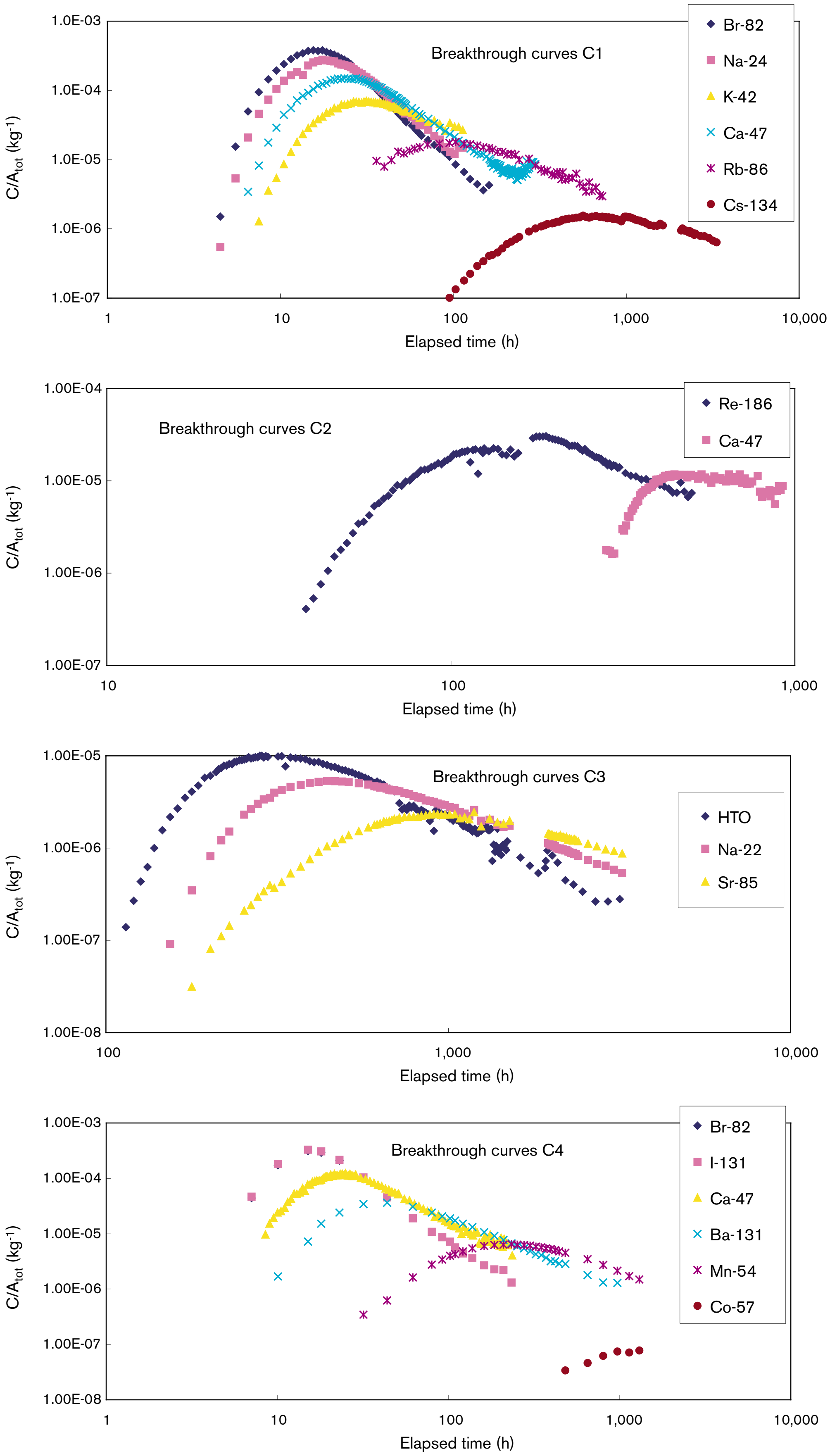


Figure 6-10. *Phase C tests with non-sorbing tracers (H-3, Br-82) and sorbing ones (Na-22, Na-24, K-42, Ca-47, Sr-85, Cs-134, Re-186, Rb-86, Mn-54, Co-57). Tests C-1 and C-4 carried out at the same location as B-2g; Test C-2 at location of B-2d; Test C-3 at location of B-2b.*

Modelling background (ITASCA)

A major difficulty in experiments such as the TRUE BS project is dimensioning tracer tests so that time scales are:

- Long enough for the retention to take place.
- Short enough for the experiment to be feasible.

Being able to assess transport time scales before performing a full-scale experiment is valuable to the project and this may be possible to do by assessing the correlation between the early time response to pumping tests (obtained in a short time) and tracer breakthrough times. Herweijer /1996/ claimed such a correlation for heterogeneous porous media. The author explained that pumping test data reveal high conductivity inter-well pathways, which also dominate the transport in the aquifer he was considering. In other words, heterogeneity, by forcing well-defined pathways, was the cause of the correlation he saw. In fractured rock, where flow path conductivities are generally highly variable, this is also likely to be the case.

Modelling objectives

This project investigates the existence and relevance of this correlation in fracture networks, focusing on the understanding of the response of the system modeled, in order to check the robustness of the "draw down-breakthrough time" relationship. The objective is to assess if this concept can be of use to help dimensioning transport experiments.

Simulations and results

Using geometrical models developed for a previous study from Äspö TRUE Block Scale data (Äspö, 1997), we simulate a constant-head test (50 m draw down at pumping well) and advective tracer tests in various fracture networks, changing both network geometry and conductor hydraulic properties. We then compare the breakthrough time for a 0.5 cm draw down (1/1000) and the arrival time for 1% of the tracer.

First, we assess the influence of the scale of heterogeneity on the correlation between the pumping test response and the tracer breakthrough times. We compute the response of six networks, with various fracture density and fracture mean radius, everything else being kept constant. For all the networks, we keep the product of the fracture density by the mean square fracture radius constant. This fixes the average number of fractures a borehole would cut. Therefore, all the networks we use would look identical if crossed by boreholes; they conform to the most robust type of data we have access to.

Figure 6-11 shows log-log plots of the relationship between the transport and flow characteristic times for four runs, with fracture mean radii varying from 3.2 m to 200 m. It shows how the degree of correlation depends on the respective scale of the fractures and of the volume of rock tested. In other terms, the correlation we are investigating may be of practical interest only if the flow paths tested include only a few fractures. In a system with many interconnected small features, the pathways between injection and recovery wells may branch in a lot of ways, adding extra tracer dispersion to the transport process, compared to a system with fewer large fractures. This means that, for a fracture field with a given "linear density" measured in boreholes, looking at the correlation between well test responses and tracer breakthroughs should yield information on the significant scale of the fracture network. This in itself would be useful, since fracture scales are quite difficult to measure in the field, with size distributions from fracture trace surveys often truncated because of the inadequate size and shape of the available sampling areas (tunnel walls and outcrops).

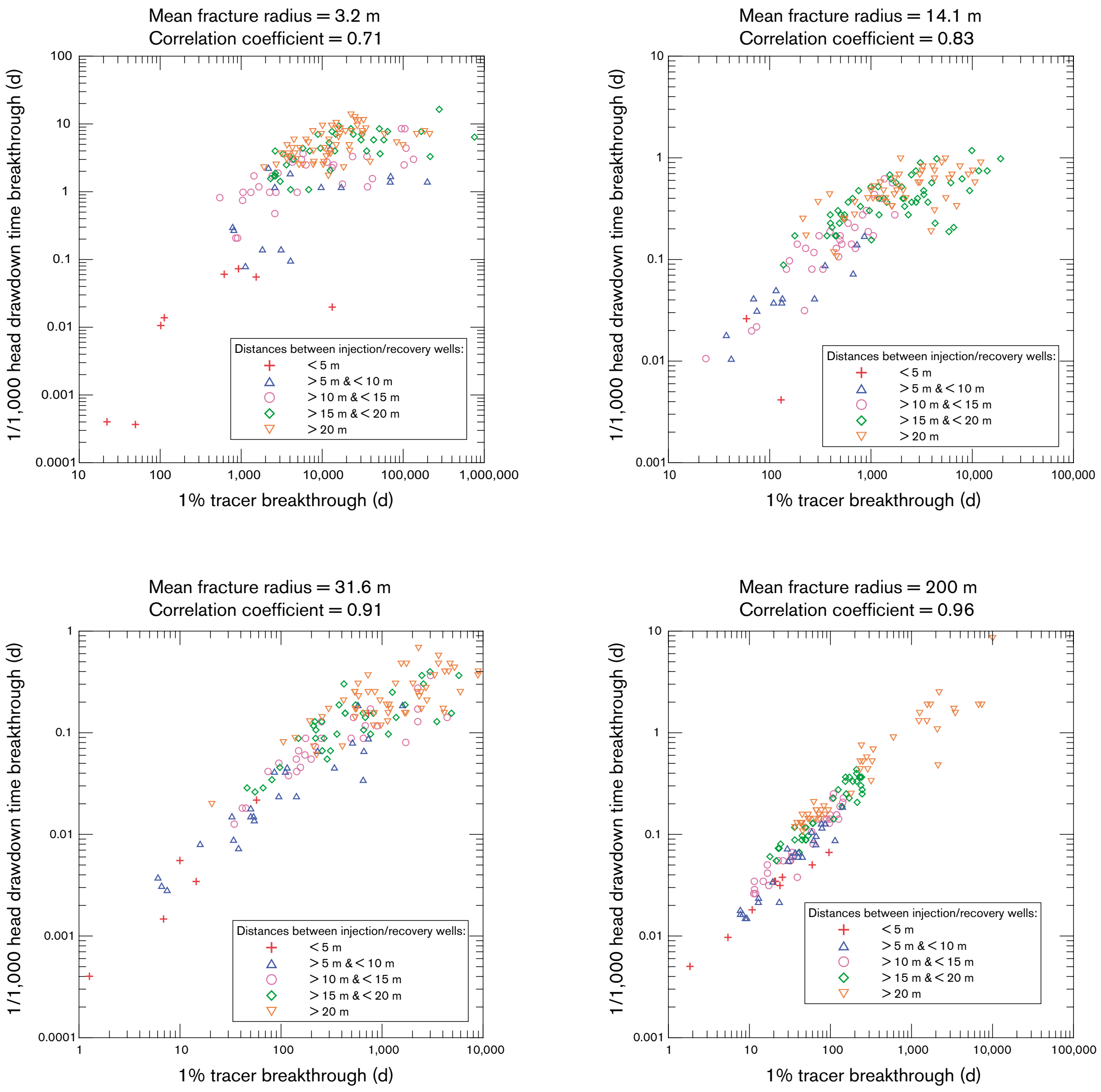
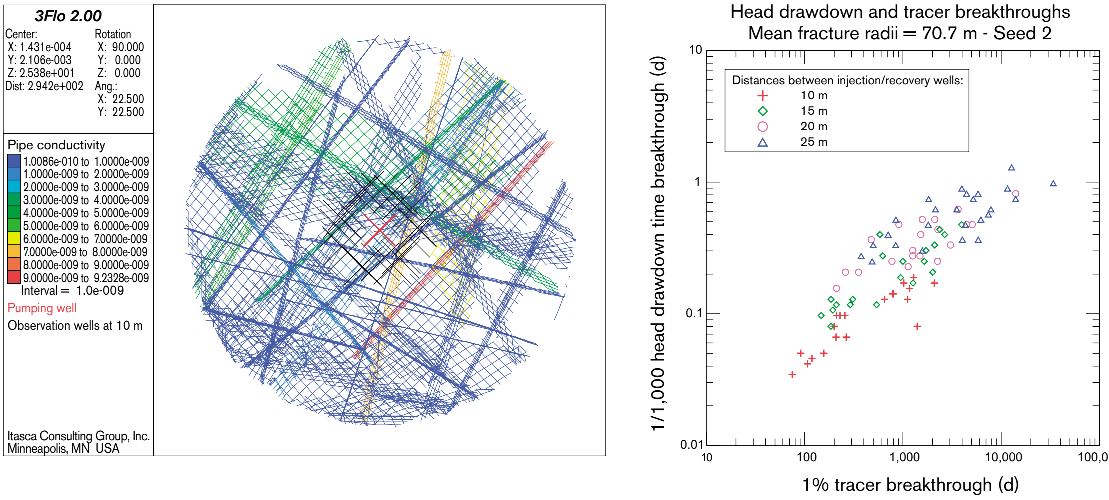


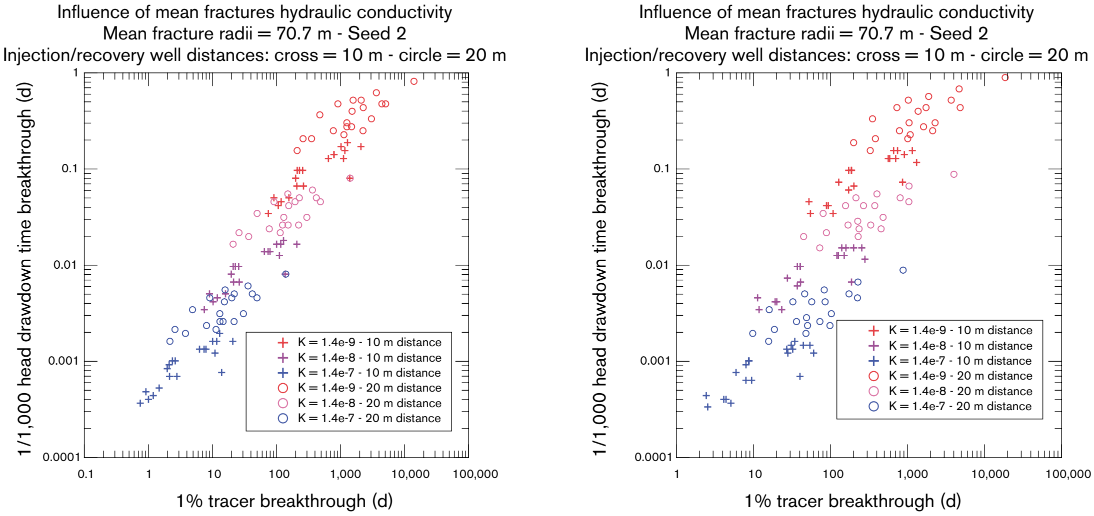
Figure 6-11. *Time for 1% head drawdown versus time for 1‰ tracer breakthrough, for various mean fracture radii.*

When investigating the effect of varying conductor hydraulic properties, using networks with fairly large radii. Figure 6-12 shows a horizontal slice through one of these networks, with a mean radius of 70 m, as well as some correlation pictures obtained with this network when varying the hydraulic properties. In summary, geometry is by far the most important factor. Incorporating matrix diffusion in a series of runs gave a little effect. This may be imputed to the fact tracking the early pressure and early tracer breakthroughs. The conclusion would certainly differ if monitoring, for example, a 50% tracer recovery.



a) 10 m thick horizontal slice through the model

b) constant aperture and conductivity



c) constant aperture, variable conductivity

d) variable aperture and conductivity

Figure 6-12. *Effect of conductor hydraulic properties – time for 1% head drawdown versus time for 1‰ tracer breakthrough.*

In terms of direct field application of the concepts discussed above (i.e. "predicting" tracer breakthrough time scales from well tests), we can expect good results if the distance between monitoring and pumping wells is not too large. Besides increasing the test duration and distances between wells may add fracture intersections and complexity into the flow and transport system and result in poorer correlation. Future adequate well test analysis techniques, using for instance a variable flow dimension approach, could allow a better understanding. The information gained from well test analysis would be the key for predicting the correlation between tracer and head draw down breakthrough times and therefore help for designing tracer tests in complex systems.

Task Force on groundwater flow and transport modelling Task 5

ANDRA is participating with three modelling teams in the Task 5 of the Task Force on groundwater flow and transport modelling. The objectives of its involvement have been presented in the previous Annual Report 1999. According to ANDRA's strategy, teams are adopting specific complementary approaches:

- ANTEA uses a dual porosity model of fractured zones and matrix with the 3D computer code "TAFFETAS" based on Mixed and Hybrid Finite Element Method.
- CEA models non sorbing flow and transport in the fracture network with the full 3D code "CASTEM 2000" (Mixed and Hybrid Finite Element Method).
- ITASCA uses a discrete fracture model (21 fractures zones with channelized flow) implemented with the code "3FLO" (Finite Elements) and a geochemical module.

Results obtained

ANTEA's analysis of the flow and transport parameters indicate that:

- Calculated concentrations are very sensitive to fracture transmissivities.
- Results are sensitive to Dirichlet boundary conditions.
- Cinematic porosity, specific storativity and dispersivity influence the calculated concentrations.

CEA's preliminary results indicate's model sensitivity to boundary conditions and to transport parameters (dispersion).

- Density effects linked with salinity become significative for deep zones.

ITASCA's flow and transport modelling results show the following:

- Simulations over-estimate the Baltic water intrusion at checkpoints.
- Integration of chemical information leads to better fit with reality.
- Sorbing transport simulation indicates precipitation-dissolution process possibly influence the hydro-geological model.

6.2.3 Japan Nuclear Cycle Development Institute

Tracer Retention Understanding Experiment

Japan Nuclear Cycle Development Institute (JNC) actively participated in the Äspö Task Force on Modelling Groundwater Flow and Transport and in the TRUE Block Scale experiment during 2000. The Task Force work involved analysis of solute transport for Task 4F, and evaluation of site scale hydrogeochemical modeling of Äspö for Task 5 /Wikberg, 1998/.

During 2000, JNC activities for the TRUE Block Scale experiment focused on development and documentation of the tracer test stage rock block conceptual model, and predictive simulations for sorbing tracers using the channel network (CN) approach.

Äspö Task Force on Modeling Groundwater Flow and Transport, Task 4F

Background

The Tracer Retention Understanding Experiments (TRUE) are part of a research programme at Äspö, the Swedish Hard Rock Laboratory, designed to study the transport of radionuclides in crystalline rock. During 2000, JNC carried out discrete fracture network solute transport analyses to resolve differences between sorbing tracer experiments carried out in the "TRUE-1" rock block and the results of stochastic discrete fracture network (DFN) simulations.

Objectives

The objective of JNC/Golder activities during 2000 were to improve the understanding of the physical and geological material properties and mechanisms behind measured sorbing and conservative tracer transport experiment results obtained within the TRUE-1 experimental programme at Äspö.

Experimental Concept

JNC/Golder team has used a combination of discrete feature network flow modeling and Laplace Transform Galerkin solute transport modeling. The processes considered in these predictive models are:

- pathways through deterministic and stochastic fractures,
- advective transport,
- dispersion within fracture planes,
- surface sorption,
- diffusive exchange between mobile and immobile zones,
- matrix diffusion,
- matrix sorption.

The extent of mobile-immobile zone exchange is quantified by effective values for transport path length, transport path width, effective porosity for the matrix material active in transport, and the thickness of the matrix material active in transport at the test time scale. Geological information clearly indicates the importance of fracture infilling such as gouge and breccia, indicating that the high porosity, low thickness assumed for matrix materials in predictive simulations are not inconsistent with what should be expected.

Results

During 2000, JNC carried out extensive simulations to determine whether assumptions of greater diffusion depth, different values of matrix porosity, or different pathway geometries could better explain the predictions made for the sorbing tracer transport experiment STT-2 during 1999. However, these simulations indicate that while it is possible to calibrate individual parameters to obtain a better match for a particular tracer, the overall assumptions used during the 1999 predictive simulations provide a good match to observed behavior (Figure 6-13 and Figure 6-14).

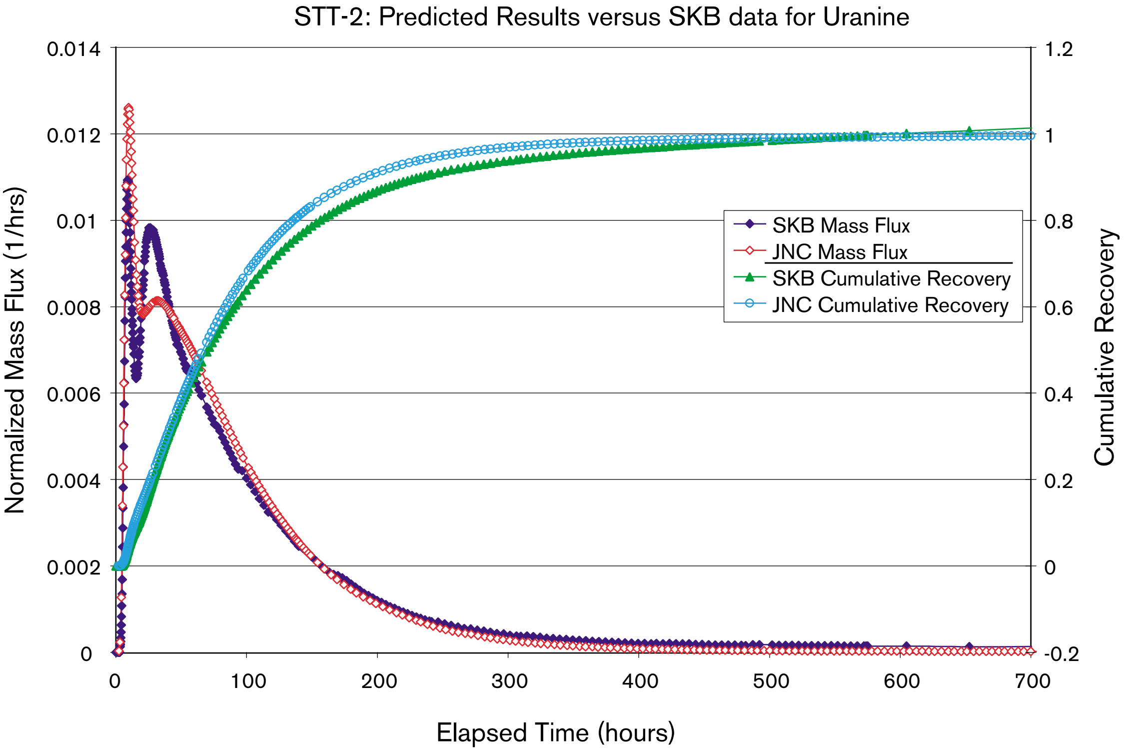


Figure 6-13. *STT-2 Prediction for Conservative Tracer Uranine.*

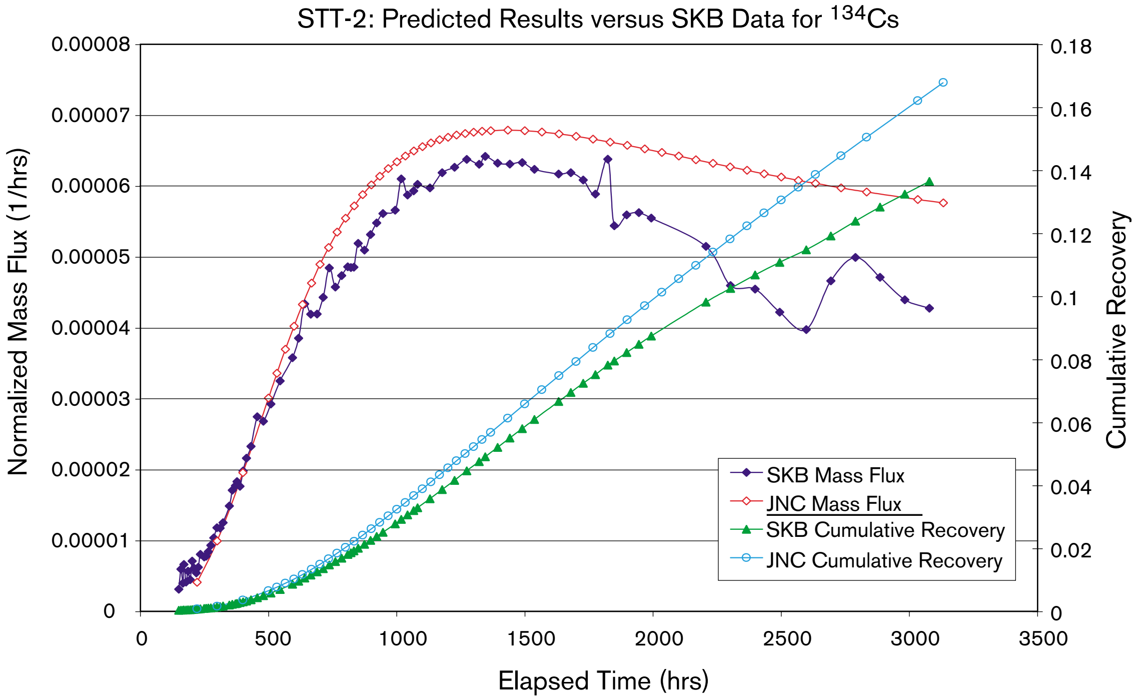


Figure 6-14. *STT-2 Prediction for Sorbing Tracer Cesium.*

Äspö TRUE Block Scale Experiment

Background

JNC has participated in the Äspö TRUE Block Scale project since 1998. In this project, SKB and its partners are characterizing a block of fractured rock at the 50 to 100 m scale, to improve the understanding of flow and transport in networks of multiple fractures. JNC has worked with the project team to formulate the project in terms of hypotheses defining to characteristic nature of flow in fracture network, and any distinctions between the processes and parameters at fracture network scales when compared to those observed at the single fracture scale of the TRUE-1 experiment

Objectives

NC's objective within the TRUE Block Scale project is to advance the understanding of the nature of flow and transport in fracture networks at 50 to 100 m scales. Toward this end, JNC participates in the project at all levels from the definition of hypotheses to be tested, support to experimental design, development of the hydrostructural model, and hydraulic and tracer test interpretation. In addition, JNC participates in the TRUE Block Scale project as the channel network (CN) modeling team.

Experimental Concept

During 2000, JNC activities were primarily in development and improvement of the site hydrostructural model, and in channel network modeling of the rock block, including the possible effect of fracture intersection zones (FIZ). Work on the hydrostructural model led to the development of the reference hydrostructural model used by the experimental and modeling teams for all project analyses. Figure 6-15 illustrates a hydrogeological interference analysis approach developed by the JNC/Golder team to support the hydrostructural model. The hydrostructural model itself is illustrated in Figure 6-16.

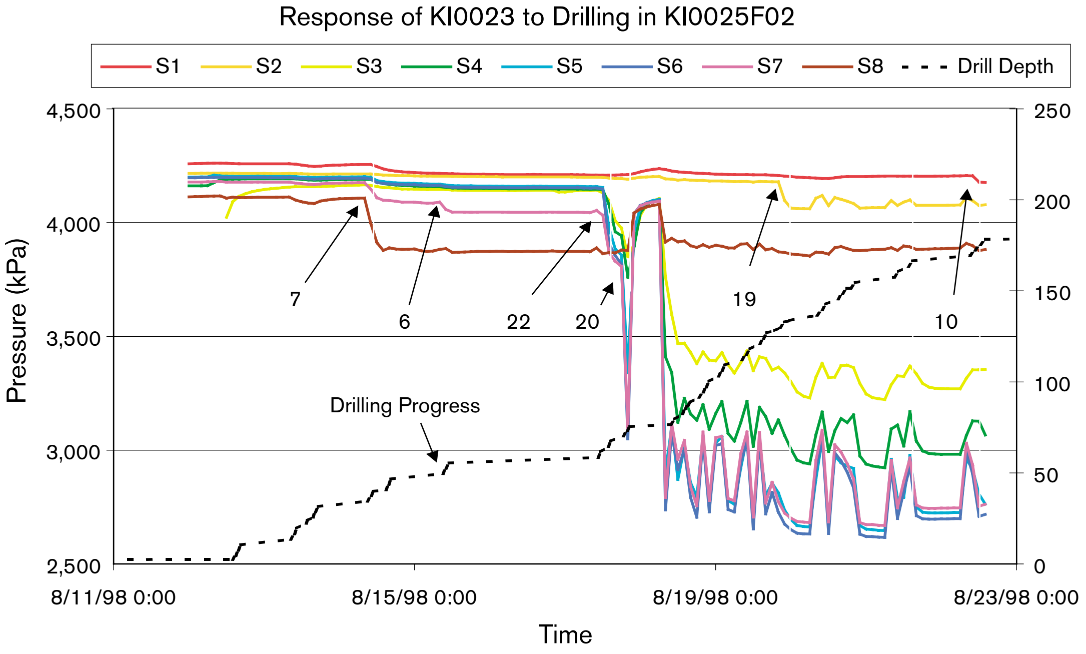


Figure 6-15. Hydraulic Interference Analysis for Development of Hydrostructural Model.

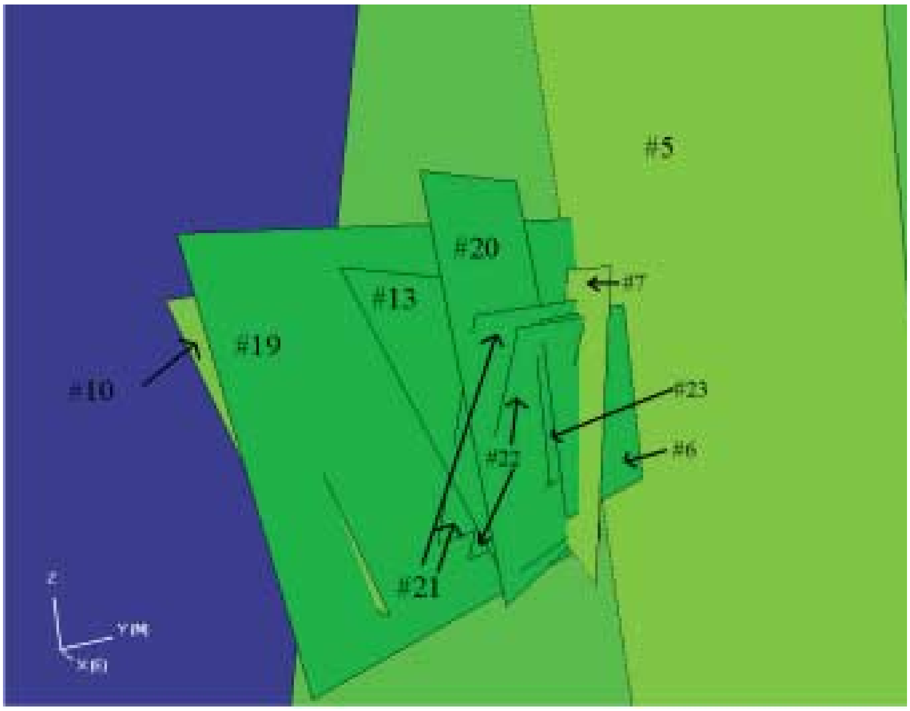


Figure 6-16. *August 2000 Update to Hydrostructural Model for TRUE Block Scale Site.*

Results

During 2000, the JNC/Golder team implemented the hydrostructural model as a channel network (CN) model. JNC then calibrated this model against both hydraulic interference and tracer experiments. This formed the basis for sorbing tracer test predictions to be carried out during 2001.

The channel network model combines the discrete deterministic structures of the hydrostructural model with stochastic background fractures as identified during the detailed site characterization phase of the project. Figure 6-17 and Figure 6-18 illustrate the hydraulic interference and conservative tracer test model calibrations carried out.

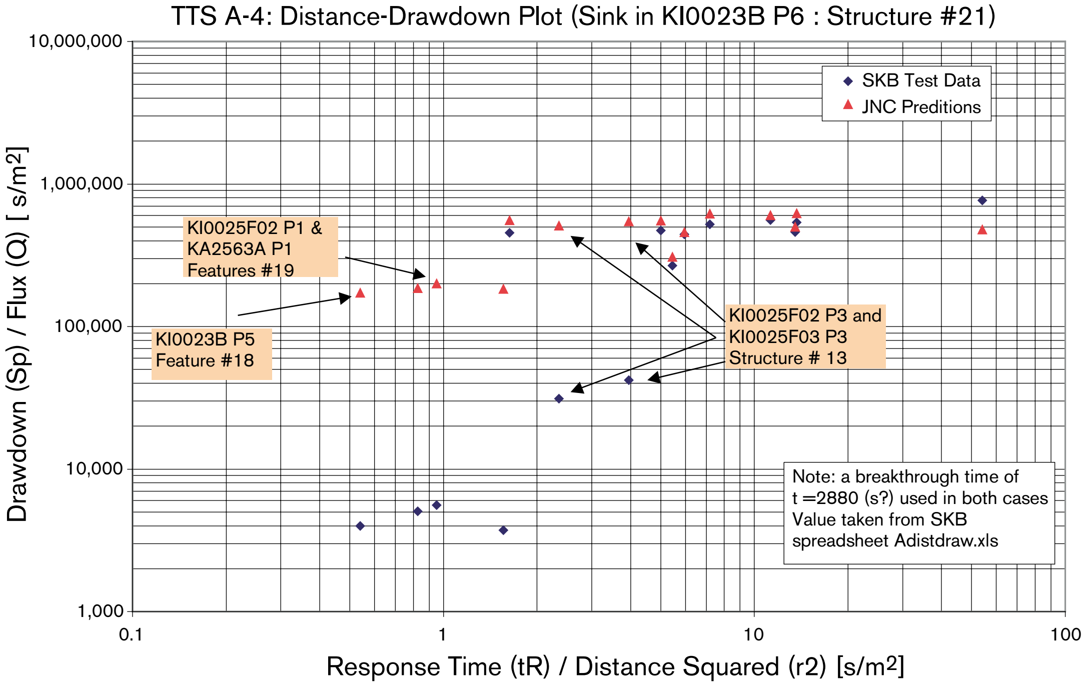


Figure 6-17. *Channel Network Model Calibration to Hydraulic Interference.*

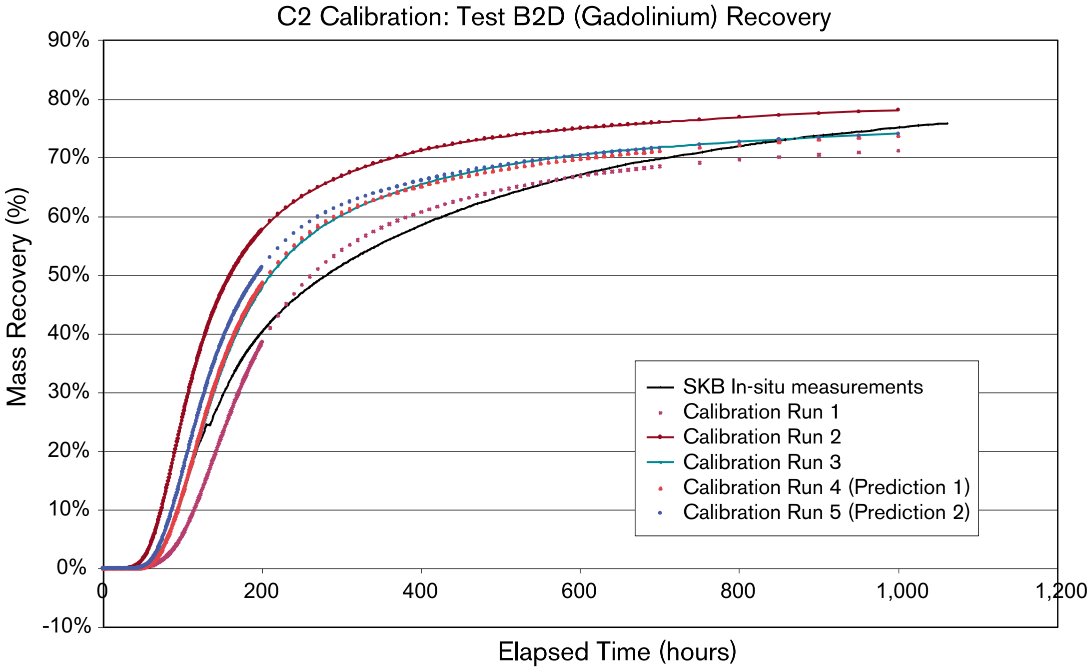


Figure 6-18. *Channel Network Model Calibration to Conservative Tracer Experiments.*

Äspö Task Force on Modeling Groundwater Flow and Transport, Task 5

Background

The Äspö Task Force on Modeling Groundwater Flow and Transport, Task 5 project has been underway since 1997. In this project, SKB and its partners have worked to develop an integrated approach to site scale hydrogeology and geochemistry. Within this project, JNC completed hydrogeological modeling of the Äspö site at the 2 km scale during 1999. During 2000, JNC focused on addressing uncertainty issues raised by previous modeling.

Objectives

The objective of JNC activities for Task 5 during 2000 was to address the uncertainty issues raised by previous hydrogeochemical modeling within the project. Work focused on three areas:

1. Uncertainty introduced to the analysis by the use of the four M3 geochemical endmembers. This was addressed by multivariate analysis for endmembers with lower residual error.
2. Limitations of the graph-theory based pathway analysis used to identify geochemical transport pathways. This was addressed by development of a new particle backtracking algorithm to improve pathway identification.
3. Uncertainties introduced to previous modeling by the use of a simplified spatial interpolation of initial conditions. This was addressed by development of a spatial interpolation approach which reflected fracture zone geochemistry patterns, and also distinguished waters under Äspö island from those beneath the Baltic.

Experimental Concept

The JNC/Golder analysis during 2000 focused on improving the discrete fracture network/channel network methodology developed for integrated hydrogeochemical analysis during 1998 and 1999. Figure 6-19 presents an outline of the approach developed to addressed uncertainty arising from end-member identification issues. In this approach, eigenvector based multi-attribute analysis was used to determine mathematically distinct end members. These end members were then updated to reflect geological and geochemical possibilities.

Results

The updating of geochemical end-members, spatial interpolation of initial conditions, and improvements to pathway analysis was able to resolve many of the remaining uncertainties in the Äspö island scale hydrogeochemical model. However, it did not eliminate all of the errors – many geochemical pathways remain unexplained, and will require further research to resolve the remaining uncertainties. Figure 6-20 illustrates one of the better geochemical breakthrough matches from the model updated during 2000.

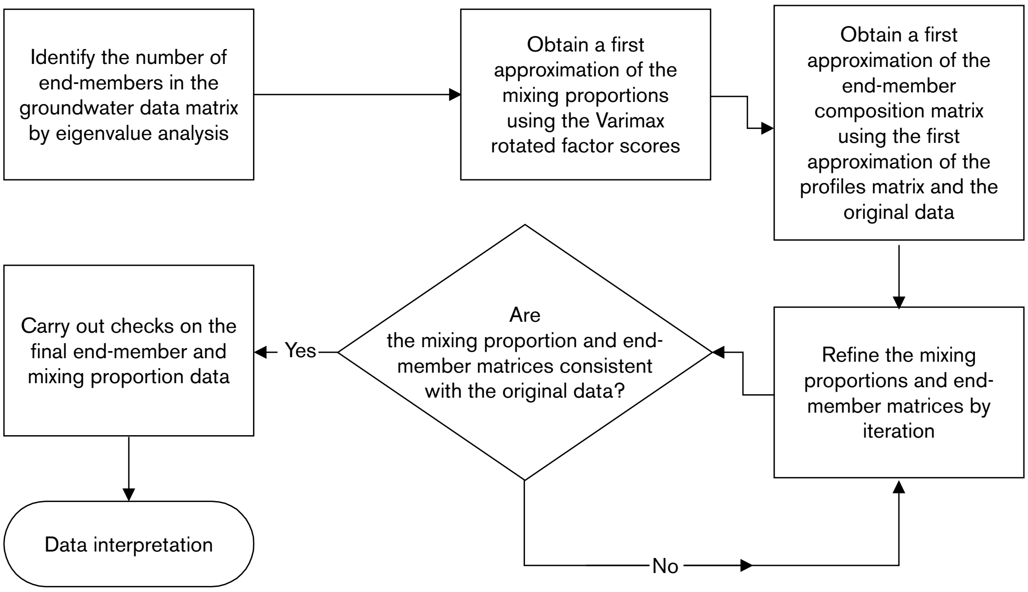


Figure 6-19. *Multi-attribute Geochemical End-member Approach.*

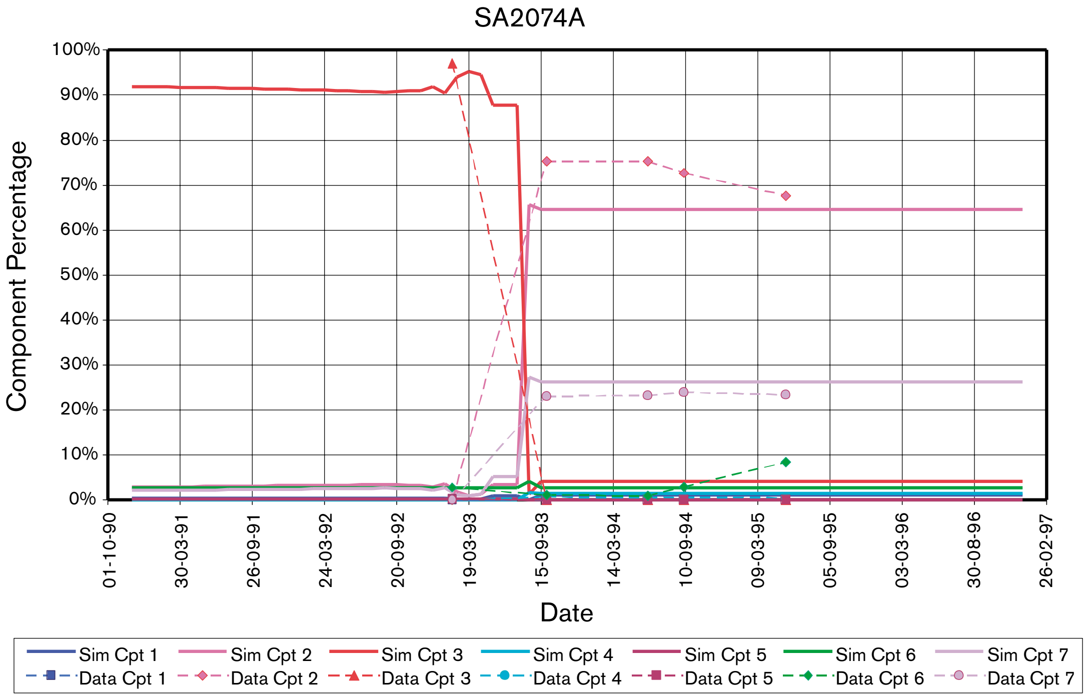


Figure 6-20. *Example Comparison of Simulated and Measured Geochemcial End-member breakthrough using updated endmembers, initial condition interpolation, and pathway analysis.*

Redox experiment in detailed scale (REX)

Objective

The main objective of the REX projects is to investigate dissolved molecular oxygen consumption by creating a controlled oxidizing perturbation to the deep rock environment at the Äspö Hard Rock Laboratory which is representative of a deep repository environment /Puigdomenech et al, 2001/.

The specific objectives are:

1. Assess the capacity of the host rock system to buffer against an oxidising disturbance.
2. Determine the kinetics (half-life) of oxygen consumption.
3. Apply quantitative descriptions of these processes that can be used in performance assessment of the repository redox stability for the post-closure phase.

REX international seminar

The REX project conducted by SKB and cofinanced by JNC and ANDRA, consists of differnent of experiments, the in-situ experiment was carried out in the Äspö Hard Rock Laboratory whereas surface laboratory experiments were conducted by the universities of Goteberg and Bradford, by the British Geological Survey and French CEA.

The purpose of the REX international seminar is to present the outcome of the entire project and to put the findings in perspective of redox conditions of importance to performance and safety assessment for disposal of radioactive waste in deep geological formations. The seminar was held in JNC Oarai engineering center on 6–9 November 2000.

Prototype Repository Project

JNC participated in the Prototype Repository Project (PRP) during 2000. JNC participated in Work packages of Emplacement of bentonite buffer, disposal of canister with heaters, backfilling of bentonite, THM modeling of buffer, backfill and interaction with near-field rock, and C modeling of buffer, backfill and groundwater.

Emplacement of bentonite buffer, disposal of canister with heaters, backfilling of bentonite

Background

JNC has performed some engineered barrier experiments. Regarding laboratory experiments, “COUPLE” and “BIG-BEN” had performed in JNC Tokai works. COUPLE was the small scale experiment /Amemiya et al, 2000/ and BIG-BEN was the full scale experiment /Chijimatsu et al, 2000a/. On the other hand, regarding in-situ experiment, Kamaishi engineered barrier experiments had performed in Kamaishi in-situ experiment site. Kamaishi experiments had two experiments that were the small scale experiment /PNC, 1994/ and the full scale one /Chijimatsu et al, 2000b/. In these experiments, JNC has used various types of sensors to measure the THM phenomena in and around the engineered barrier system (EBS). JNC has a wealth of experience and knowledge for applicability of the measurement techniques. It is considered that this information, which JNC has, is useful to the PRP.

Objectives

JNC review the sensor layout in the borehole, and provide the useful information about the application of the sensors to the PRP to obtain the useful experimental data in the PRP.

Results

JNC reviewed the report on instrumentation of buffer and backfill for measuring THM processes. This report described the sensor layout plan, JNC has responded to the report with some comments.

Humidity sensors

At Kamaishi experiments, 40 psychrometers (PST-55, WESCOR,) and 11 humidity sensors (HMP 233H, VAISALA) were buried in buffer /Sugita et al, 1997/. Every sensor was no armed type. After 260 days heating and 190 days cooling, 9 psychrometers and 4 humidity sensors were out of order.

As for psychrometer, 5 were damaged before heating, 3 during the heating (drying) phase, and 1 during wetting. Psychrometer had 2 thermocouples (TC), one was used for temperature measurement, the other was for cooling by the Peltier effect. The former TCs were protected enough during THM test. But, 3 of 5 sensors which damaged before heating, were damaged not only the TC for cooling, but also TC temperature measurement.

As for HMP233H, one was damaged before heating test, 3 were during the drying phase.

Psychrometer (PST-55) and HMP 233H have disadvantage for durability compared with other sensors of PRP. But without initial damages, 88% of PST-55 and 70% of HMP 233H worked fairly well for 450 days.

As for psychrometer, almost damages occurred during drying phase. Main reason was that the vapor movement in buffer might attack the TC for cooling. The measurement of backfill saturation by psychrometer as shown in the plan of PRP is reasonable.

At Kamaishi experiments, two types of humidity sensor, PST-55 and HMP 233H, were set in separate location, so we could not compare the data acquired by different way. It is important that different type sensors set at same condition in order to compare or examine the accuracy of each measuring method.

Thermocouple

The target measurement region of temperature is significant to select sensor. In the PRP, the target temperature will be up to 120 degrees centigrade. T type thermocouple sensor has adequate measuring range. E type and K type have too wide measuring range. In Kamaishi experiment, all K type thermocouple had drift of measurement data. T type had measured good data.

Report on instrumentation of buffer and backfill for measuring THM processes

In the PRP, measurement data will be used for analysis by some numerical codes. For the validation of the numerical codes, the detail and dense measurement data are needed.

Regarding the sensor positions in a deposition hole, the proposed sensor layout had no sensor at the edge of the bottom end of the deposition hole. JNC suggested that the data of temperature, at the least, is necessary to obtain the boundary condition. Around the heater, the contour map of water content may be high density, therefore, dense emplacement of water content sensor could monitor the complec distribution of water content in the buffer well.

Regarding sensor positions of the cross section between the deposition hode sections in the tunnel, the proposed sensor layout had no sensor in the interface between side rock surface and the buffer. JNC suggested that the data of temperature, at the least, is necessary to obtain the boundary condition.

THM modeling of buffer, backfill and interaction with near-field rock

Background

JNC has validated the coupled THM analysis numerical code "THAMES". THAMES was originally developed by Professor Ohnishi, Kyoto University /Ohnishi et al, 1985/. JNC has validated the THAMES with Hazama Corporation and Kyoto University. THAMES was applied to the simulation of the coupled THM phenomena in and around the EBS in the second progress report on research and development for the geological disposal of HLW in Japan.

Objectives

The main objective is to predict THM processes in and around the EBS by applying existing models, and to compare the prediction with the obtained data. This will demonstrate the validity of the existing model and the capacity of numerical modeling of the performance of the bentonite buffer and the backfill.

Results

Numerical analysis code THAMES

1) Analysis objective.
Analysis of the coupled thermal, hydraulic and mechanical process is carried out with the computer code named THAMES. THAMES is a finite element code for analysis of coupled thermal, hydraulic and mechanical behaviors of a saturated-unsaturated medium. THAMES is extended to take account of the behavior in the buffer materials such as the water flow due to thermal gradient and the swelling phenomena. The unknown variables are total pressure, displacement vector and temperature. The quadratic shape function is used for the displacements and linear one is used for total pressure and temperature.

2) Governing equations of coupled T-H-M process.
The mathematical formulation for the model utilizes Biot's theory, with the Duhamel-Neuman's form of Hooke's law, and energy balance equation. The governing equations are derived with the fully coupled thermal, hydraulic and mechanical relationships.

2.1) Governing equations of original THAMES.

The governing equations of original code are derived under the following assumptions:

(a) The medium is poro-elastic.

(b) Darcy's law is valid for the flow of water through a saturated-unsaturated medium.

(c) Heat flow occurs only in solid and liquid phases. The phase change of water from liquid to vapor is not considered.

(d) Heat transfer among three phases (solid, liquid and gas) is disregarded.

(e) Fourier's law holds for heat flux.

(f) Water density varies depending upon temperature and the pressure of water.

Governing equations for a coupled thermal, hydraulic and mechanical problem proposed by Ohnishi et al (1985) are shown in equation (1) to (3). This model was verified with the available analytical and experimental results. These equations are used by means of a total head expression such as,

$$\left[\frac{1}{2}C_{ijkl}\left(u_{k,l}+u_{l,k}\right)-\beta\delta_{ij}\left(T-T_o\right)+\chi\delta_{ij}\rho_f g\psi\right]_{,j}+\overline{\rho_s}b_i=0 \tag{1}$$

$$\left\{\rho_f k(\theta)_{ij}h_{,j}\right\}_{,i}-\rho_{fo}nS_r\rho_f g\beta_P\frac{\partial h}{\partial t}-\rho_f\frac{\partial\theta}{\partial\psi}\frac{\partial h}{\partial t}-\rho_f S_r\frac{\partial u_{i,i}}{\partial t}+\rho_{fo}nS_r\beta_T\frac{\partial T}{\partial t}=0 \tag{2}$$

$$\begin{aligned}&\left(\rho C_v\right)_m\frac{\partial T}{\partial t}+nS_r\rho_f C_{vf}V_{fi}T_{,i}-K_{Tm}T_{,ii}\\&-nS_rT\frac{\beta_T}{\beta_P}k(\theta)h_{,ii}+\frac{1}{2}(1-n)\beta T\frac{\partial}{\partial t}\left(u_{i,j}+u_{j,i}\right)=0\end{aligned} \tag{3}$$

2.2) Governing equations of extended coupled T-H-M model for buffer material (Chijimatsu et al, 2000c).

The behavior of the buffer material is influenced by the interdependence of thermal, hydraulic and mechanical phenomena. To treat the water/vapor movement and heat induced water movement, the continuity equation used in the extended THAMES code is as follows;

$$\begin{aligned}&\left\{\xi\rho_l D_\theta\frac{\partial\theta}{\partial\psi}\left(h_{,i}-z_{,i}\right)+\left(1-\xi\right)\frac{\rho_l^{\,2}gK}{\mu_l}h_{,i}\right\}+\left\{\rho_l D_T T_{,i}\right\}_{,i}\\&-\rho_{lo}nS_r\rho_l g\beta_P\frac{\partial h}{\partial t}-\rho_l\frac{\partial\theta}{\partial\psi}\frac{\partial h}{\partial t}-\rho_l S_r\frac{\partial u_{i,i}}{\partial t}+\rho_{lo}nS_r\beta_T\frac{\partial T}{\partial t}=0\end{aligned} \tag{4}$$

where D_θ is the isothermal water diffusivity, θ is the volumetric water content, ψ is the water potential head and K is the intrinsic permeability. The symbol ξ is the unsaturated parameter so that $\xi = 0$ at the saturated zone, $\xi = 1$ at the unsaturated zone. The symbol μ_l is the viscosity of water, ρ_l is the density of water, g is the gravitational acceleration. D_T is the thermal water diffusivity, n is the porosity, S_r is the degree of saturation, β_P is the compressibility of water, β_T the thermal expansion coefficient of water and z is the elevation head. u_i is the displacement vector, T is temperature, h is the total head and t is time. The subscript 0 means the reference state. This equation means that the water flow in the unsaturated zone is expressed by the diffusion equation and in the saturated zone by the Darcy's law.

The energy conservation equation has to treat the energy change by evaporation. The equation is given as,

$$\begin{aligned}&(\rho C_v)_m \frac{\partial T}{\partial t} + nS_r \rho_l C_{vl} V_{li} T_{,i} - K_{Tm} T_{,ii} + L\left\{ D_{\theta v} \frac{\partial \theta}{\partial \psi}(h_{,i} - z_{,i}) \right\}_{,i} \\ &+ nS_r T \frac{\beta_T}{\beta_P} \left\{ \xi D_\theta \frac{\partial \theta}{\partial \psi}(h_{,i} - z_{,i}) + (1-\xi)\frac{\rho_l g K}{\mu_l} h_{,i} + D_T T_{,i} \right\}_{,i} \\ &+ \frac{1}{2}(1-n)\beta T \frac{\partial}{\partial t}(u_{i,j} + u_{j,i})\delta_{ij} = 0\end{aligned} \tag{5}$$

where $(\rho C_v)_m$ is the specific heat of the material consisting of water and the soil particles, C_{vl} is the specific heat of water, V_{li} is the velocity vector of water, K_{Tm} is the thermal conductivity of consisting of water and the solid particles, L is the latent heat of vaporization per unit volume and $D_{\theta v}$ is the vapor diffusivity.

The equilibrium equation has to take the swelling behavior into account.

$$\left[\frac{1}{2} C_{ijkl}(u_{k,l} + u_{l,k}) - F\pi\delta_{ij} - \beta\delta_{ij}(T - T_o) + \chi\delta_{ij}\rho_l g(h - z) \right] + \rho b_i = 0 \tag{6}$$

where C_{ijkl} is the elastic matrix, ρ is the density of the medium and b_i is the body force. χ is the parameter for the effective stress, $\chi = 0$ at the unsaturated zone, $\chi = 1$ at the saturated zone. The symbol F is the coefficient relating to the swelling pressure process and $\beta = (3\lambda + 2\mu)\, \alpha_s$, where λ and μ are Lame's constants and α_s is the thermal expansion coefficient.

The swelling pressure π can be assumed to be the function of water potential head (ψ) as follows;

$$\pi(\theta_1) = \rho_l g(\Delta\psi) = \rho_l g(\psi(\theta_1) - \psi(\theta_0)) = \rho_l g \int_{\theta_o}^{\theta_1} \frac{\partial \psi}{\partial \theta} d\theta \tag{7}$$

where θ_0 is the volumetric water content at the initial state. This is based on the theory that swelling pressure is equivalent to the water potential.

3) Numerical techniques.

The Galerkin type finite element technique is employed to formulate a finite element discretization. In order to obtain stable solution, linear isoparametric elements are used to represent the behavior of total head h and temperature T. Quadratic isoparametric elements are used to express displacement u_i. In order to integrate time derivatives, a time weighting factor is introduced, and thus, any type of finite difference scheme may be applied.

4) Validation of THM model THAMES.

JNC has performed some EBS experiments. The results of those experiments are used to validate the analysis code THAMES. Regarding fundamental behavior, especially the expression of the hydraulic behavior of the buffer is complex problem. JNC has performed pressurized infiltration test. From the comparison between the measured data and the analysis, it is clarified that THAMES can evaluate the infiltration phenomena at both the atmospheric pressure and the pressurized condition /Chijimatsu et al, 2000c/.

A two-dimensional axisymmetric model is used to analyze the BIG-BEN experiment. THAMES can explain the distribution of temperature and water content well. In THAMES, the calculated swelling pressure depends on the change of the water potential. The water contents can be represented well by the numerical calculation. However, regarding swelling behavior, THAMES can not explain transient situation well. Therefore, the other factors in the mechanism of the swelling pressure may exist. And furthermore, relation between water potential and water content is important for the swelling pressure simulation by THAMES.

Applicability of the coupled thermo-hydro-mechanical model was also validated with data under the actual rock mass conditions that were obtained from a coupled thermo-hydro-mechanical experiment at the in-situ test site of the Kamaishi Mine /Chijimatsu et al, 1999a/. Those results of experiments have been compared with results of analyses conducted with the coupled thermo-hydro-mechanical model /Chijimatsu et al, 1999b/. The calculated temperature rise closely matches with measured results. The calculated water content change is also similar to the measured results. The measured water content at the point 150 mm from the heater (middle part) increases at first and then goes down. It is considered that the buffer at the middle part is wetted at first, and as time passed, this portion of the buffer begins to dry because water moves further from the heater. This phenomenon cannot be simulated in this analysis. The calculated water movement is smoother than that of measured one. It is considered that the reason of this discrepancy is due to use of inappropriate property of the thermal water diffusivity, i.e., the thermal water diffusivity should be a function of water content because the decreasing of water content near heater due to thermal effect is simulated well. However, simulation results agree well with measured results as whole, and it is believed that the developed models can be applied in an assessment of the coupled thermo-hydro-mechanical phenomena.

Preliminary analysis of PRP

JNC has prepared the preliminary analysis of PRP. Preliminary analysis is 2 dimensional axial-symmetrical analysis. Figure 6-21 shows the analysis model for preliminary analysis.

Figure 6-22 shows the finite element mesh for analysis. The upper and bottom boundary conditions are constant temperature and constant water pressure. The side boundary condition is adiabatic condition and no flux. All boundaries are fixed.

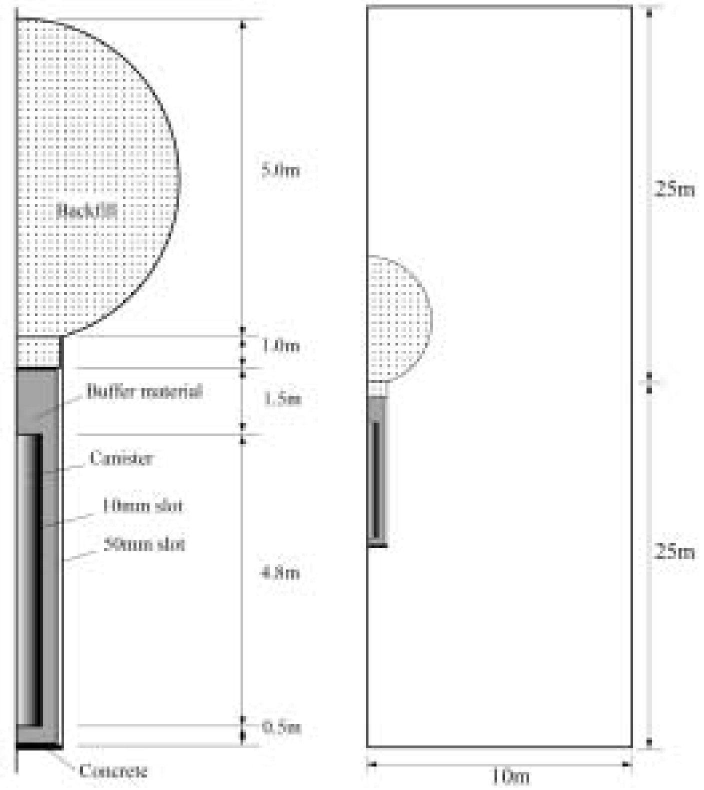


Figure 6-21. *Analysis for model for preliminary analysis.*

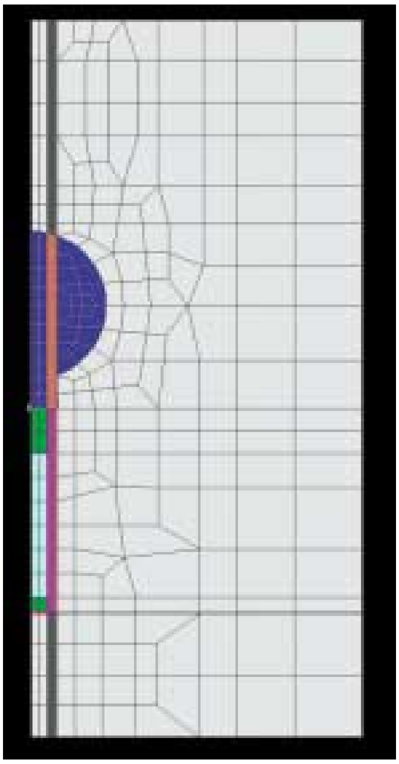


Figure 6-22. *Finite element mesh.*

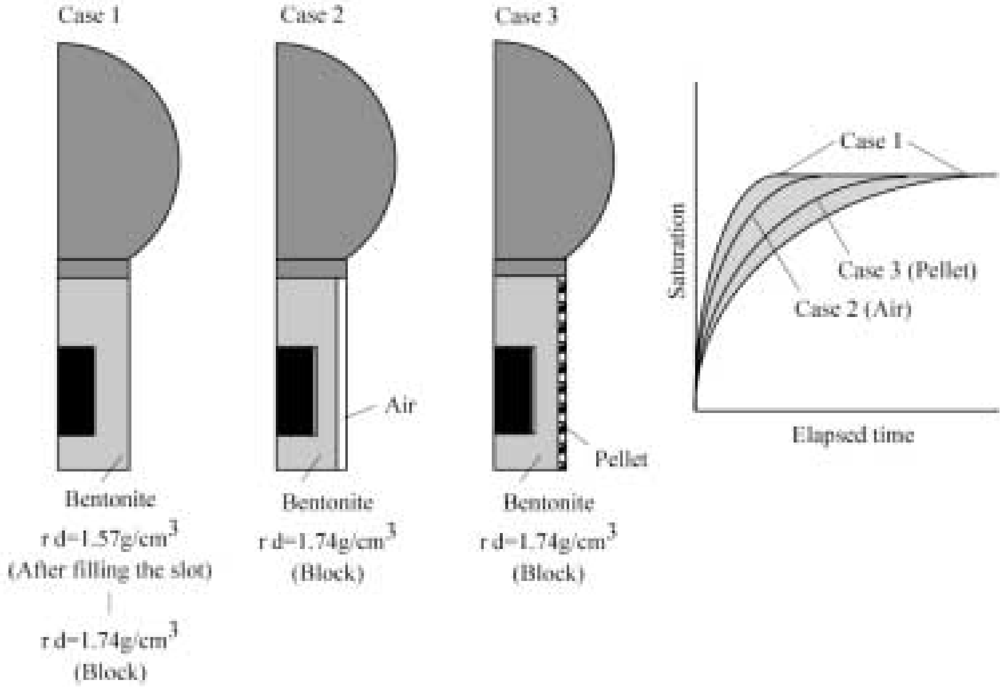


Figure 6-23. *Analysis step.*

JNC showed the analysis step for the preliminary analysis in the Modeling Meeting WP3 in Lund in Sweden. Figure 6-23 shows the analysis step. In the Case1, the gap between bentonite block and rock mass in the test pit is filled with bentonite block. In the Case2, the gap remains. In Case3, the gap is filled with the pellets and air. The expected saturation behaviors in the test pit are shown in Figure 6-23, too. We think that the Case1 will cover the expected saturation behaviors in the test pit.

C modeling of buffer, backfill and groundwater

Background

Chemical processes are one of the significant processes for assessing the migration of nuclides of HLW in performance assessment (PA). JNC considers that THM analysis has to be evolved to THMC analysis. However, chemical processes are not simple. We have to select the significant chemical processes to consider. We also need the database for the selected chemical processes. Therefore, JNC has just started the studies for chemical processes for THMC.

Objectives

To clarify the main chemical processes for performance assessment in HLW.

Results

JNC has just started the validation of THAMES to add the function for considering chemical processes. During 2000, JNC has discussed the concept for adding the function (see Figure 6-24). THC processes have been studied by some organizations. For example, the changes of porosity were key issues. Lawrence Livermore National Laboratory

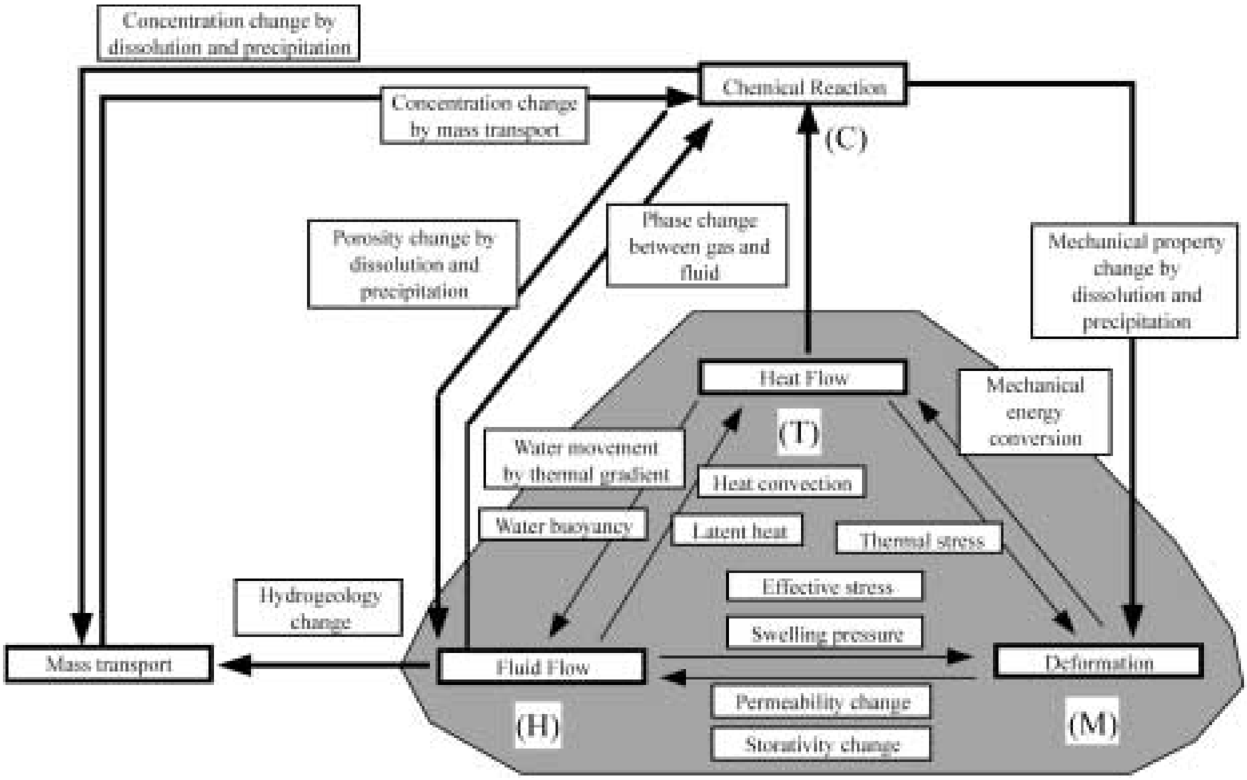


Figure 6-24. *Outline of coupled THMC processes.*

in USA (LLNL) showed one example of THC analysis /Glassley, 2000/. In this analysis, they showed the appearance of low porosity area over the HLW in host rock. In 2001, JNC will start the progress for adding the chemical processes.

6.2.4 BMWi

Background

In addition to the German research activities related to final disposal of radioactive waste in rock salt, the objective of the cooperation in the Äspö HRL programme is to complete the knowledge on other potential host rock formations for radioactive waste repositories. The work comprises investigations on two-phase flow, groundwater flow and solute transport, geochemistry, and on developing and testing of instrumentation and methods for underground rock characterization. Six research institutions are performing the work on behalf of BMWi: BGR, FZK, FZR, GRS, Technical University Clausthal, and University Stuttgart.

Two-phase and groundwater flow

Two-phase flow investigations

The two-phase flow project carried out by BGR and GRS during the past years was completed. During the first half of year 2000, the final experiment with tracers in the water phase and in the gas phase was conducted. The equipment is shown schematically in Figure 6-25. The final report is due to be concluded in 2001.

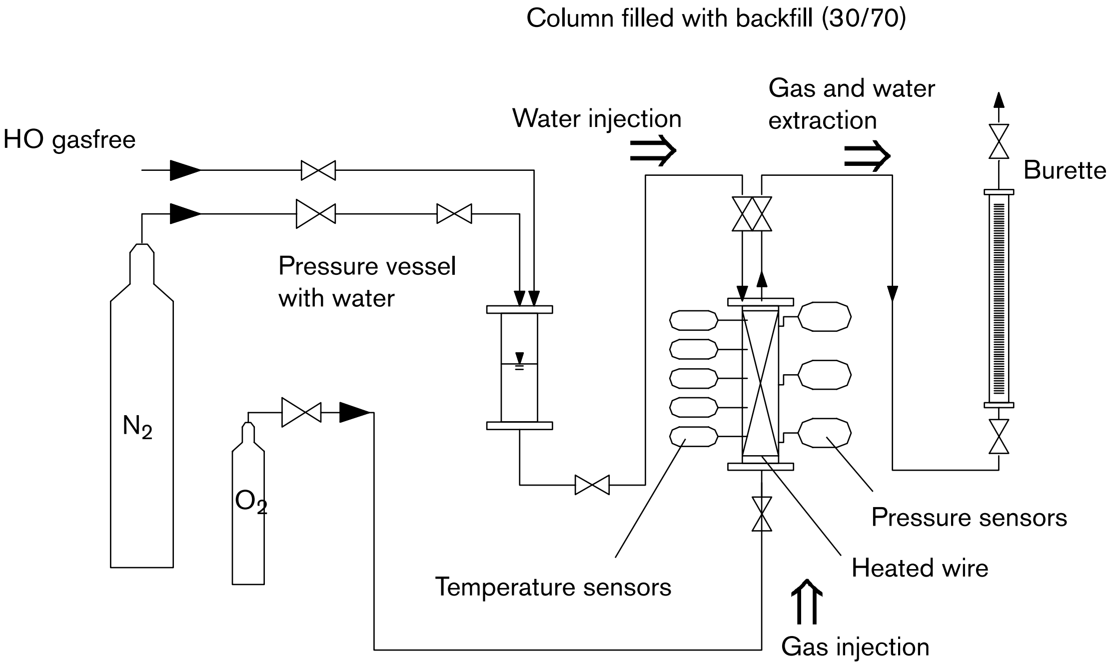


Figure 6-25. *Non-isothermal two-phase flow test equipment.*

In co-operation with KTH, University Stuttgart started a project with the aim to further improve the numerical tools for calculating gas-water flow in fractured and porous media. The objectives are to further develop the methods for describing two-phase flow processes in single fractures and to develop up-scaling methods for transferring the constitutive relations from microscale to macroscale. Furthermore, data from the Äspö HRL are used to generate geostatistical models. During the first half-year of the project duration, determination of up-scaling parameters and constitutive relationships for local heterogeneities have been initiated. In order to evaluate whether gas migration is dominated on different scales by main flow paths, the upscaled parameters will be applied to fractured systems.

Task Force on modelling of groundwater flow and transport of solutes

BGR continued the activities in the Task Force on Modelling of Groundwater Flow and Transport of Solutes by modelling and interpreting the behaviour of radioactive and sorbing tracers in the TRUE test field (Task #4E/F). The results are summarized in the Report "Modelling Reactive Radioactive and Sorbing Tracer Tests in Fractured Rock". In Task #5, Hydrogeological and Hydrochemical Modelling, a flow and transport model with 14 intersecting fracture zones was developed and used to calculate changes in flow velocity and concentration gradients resulting from tunnel construction.

Actinide migration

The FZK/INE investigations are focusing on sorption and migration of radionuclides, especially actinides, in fractured rock. To guarantee as realistic conditions as possible, the experiments are designed to be compatible with those carried out in the CHEMLAB II probe.

Objectives

The objectives of the experiments to:

- to investigate the applicability of radionuclide retention coefficients measured in laboratory batch experiments for in situ conditions,
- to validate the radionuclide retardation measured in laboratories by data from in situ experiments in rock,
- to demonstrate reliability and correctness of laboratory data under conditions prevailing in the natural rock,
- to reduce uncertainties in the retardation properties and the governing processes for americium, neptunium and plutonium.

Experimental Concept

In a first step, the experimental set-up was designed and some preliminary sorption experiments with fracture filling material and granite, respectively, and with groundwater from the area of CHEMLAB II were conducted in the laboratory at INE. To run the migration experiments in CHEMLAB II, a drill core sample with a fracture is placed in an autoclave. Core samples with a continuous fracture are chosen and placed in a sleeve of stainless steel. The periphery is filled with epoxy resin. The top and the bottom ends are closed with acrylic glass covers sealed relative to the stainless steel sleeve with an o-ring. The lids are equipped with bores for feeding and extracting groundwater lines.

The tightness of the autoclaves was tested in laboratory experiments, indicating leak-tightness up to 60 bar of groundwater pressure. Since the fluid pressure in CHEMLAB II is about 27 bar, no leakage of the autoclaves is to be expected under in situ conditions. A total of three autoclaves of appropriate dimensions were prepared from the core samples available and can now be used for laboratory and in situ experiments.

In order to evaluate actinide breakthrough through the fractured rock samples and actinide recovery as a function of the eluted groundwater volume, the hydraulic properties of fractured rock samples are investigated at INE. HTO is used as inert tracer; dependences of the breakthrough from the applied flow rates are recorded.

At Äspö HRL an inert gas glovebox was installed close to the CHEMLAB II drillhole (Figure 6-26). Tubing from the core in the CHEMLAB probe ends in the glovebox. The box contains a sample collector and a balance for recording the breakthrough as well as additional equipment required for groundwater sample preparations.

Based on geochemical model calculations, actinide tracer cocktails are prepared according to the maximum solubilities of the actinides. The isotopes Pu-244, Am-243, and Np-237 are chosen due to their long half-lives and low specific activity. In order to apply in the migration experiments cocktails with a composition corresponding to the natural groundwater, the cocktails are prepared using groundwater from Äspö HRL. The long-lived actinide concentrations in the "ÄSPÖ cocktail" are as follows:

Pu-244	approx. 1×10^{-8} mol/l
Am-243	approx. 1×10^{-6} mol/l in laboratory, 1×10^{-8} mol/l at Äspö
Np-237	approx. 1×10^{-5} mol/l

Total α-activity of the cocktail amounts to 1.8×10^{4} Bq/l.

Figure 6-26. *INE glovebox installed in a container close to CHEMLAB II drillhole (right).*

Results

Laboratory migration experiments

One autoclave with embedded drill core was used in laboratory actinide migration tests applying the same conditions as expected in the Äspö HRL. The measured effective pore volume of the fracture in the drill core was 1 ml.

By use of a calibrated sample loop, the actinide cocktail having a pH = 7 was injected. The flow rate was 0.3 ml/h (7.2 ml/day). Eluted groundwater was collected in samples of 1.5 ml. These samples were filtrated (450 nm) and analyzed due to the total α-activity by Liquid Scintillation Counting (LSC). By means of a-spectroscopy, Np-237 and Am-243 were distinguished. The total Am-243 concentration of eluted water was $1x10^{-11}$ mol/l. Np recovery was 26% of the injected quantity (Figure 6-27). The breakthrough curve was determined from the mass of the groundwater samples and the measured activity (concentrations). The eluted groundwater volume in this experiment amounted to 60 to 80 ml.

The measured pH value in the eluted water was similar to that in the injected water, the Eh was +20 mV. Additional experiments showed significantly lower Np concentration in the eluted water. However, in some experiments the measured Eh was in the range of –200 mV. This finding is related to the limited redox buffer capacity of the groundwater. These findings support the hypothesis that Np(V) is reduced to Np(IV) on the inner surfaces of the rock sample and subsequently is sorbed.

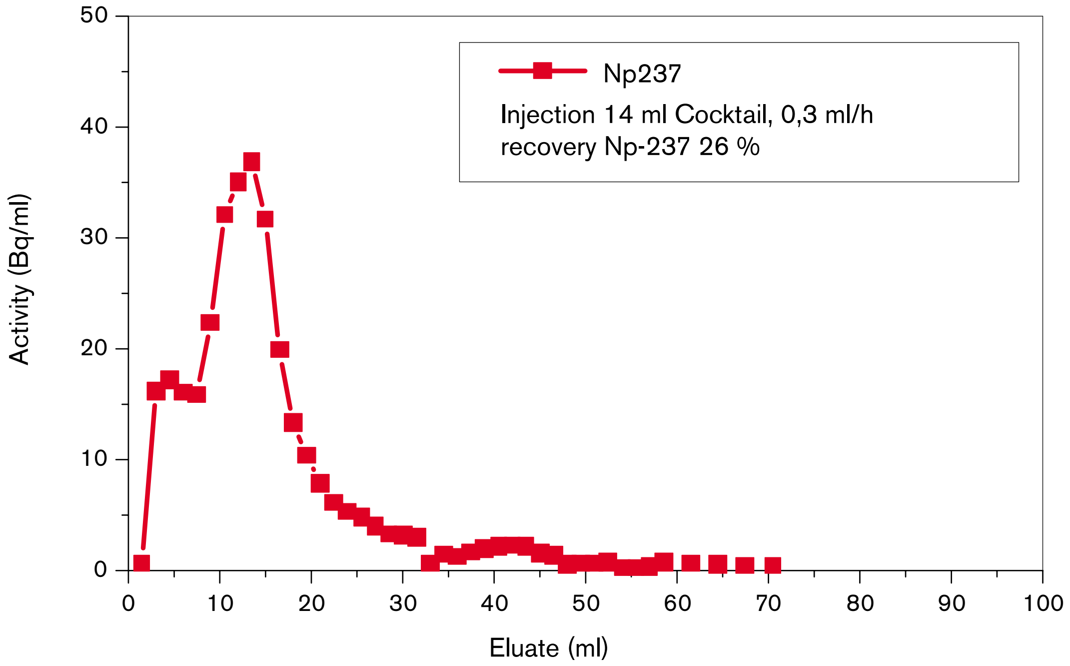


***Figure 6-27.** Np-237 breakthrough curve measured in the first INE experiment.*

In situ migration experiment

After installation of the glovebox, test runs were performed. The first in situ actinide migration experiment was started in Äspö HRL in October 2000. A 100 ml reservoir containing the actinide cocktail was inserted into the CHEMLAB II probe. In order to have an online test method for controlling the experiment, in addition to the actinides the cocktail was spiked with HTO. CHEMLAB II was equipped with the drill core autoclave and the reservoir at BASELAB laboratory. It was put in place, coupled to the glove box and a test run was performed for 5 days. After successful operation, a volume of 15 ml of actinide cocktail from the reservoir was injected into the fractured rock sample at a flow rate of 0.3 ml/h. Injection of this volume required 50 hours, afterwards natural groundwater was pumped for another 5 days at constant flowrate. After this period, it was intended to increase the flowrate. However, due to a technical defect of the CHEMLAB II probe the experiment had to be interrupted. The eluted groundwater samples were transferred to INE. Breakthrough curves for the HTO tracer and for the total a-activity are shown in Figure 6-28.

The measured pH in the eluted samples was pH = 7, Eh ranged from +30 to –60 mV. Figure 6-28 shows the measured activity in the eluted samples after filtration by 450 nm filters. ICP-MS measurements resulted in Am-243 and Pu-244 concentrations below the detection limit of $1x10^{-12}$ mol/l. These findings indicate that only Np-237 contributes to the measured α-concentration. This result is equivalent to the results obtained from the first laboratory migration experiment. Np-237 recovery was computed to be 40% of the injected quantity.

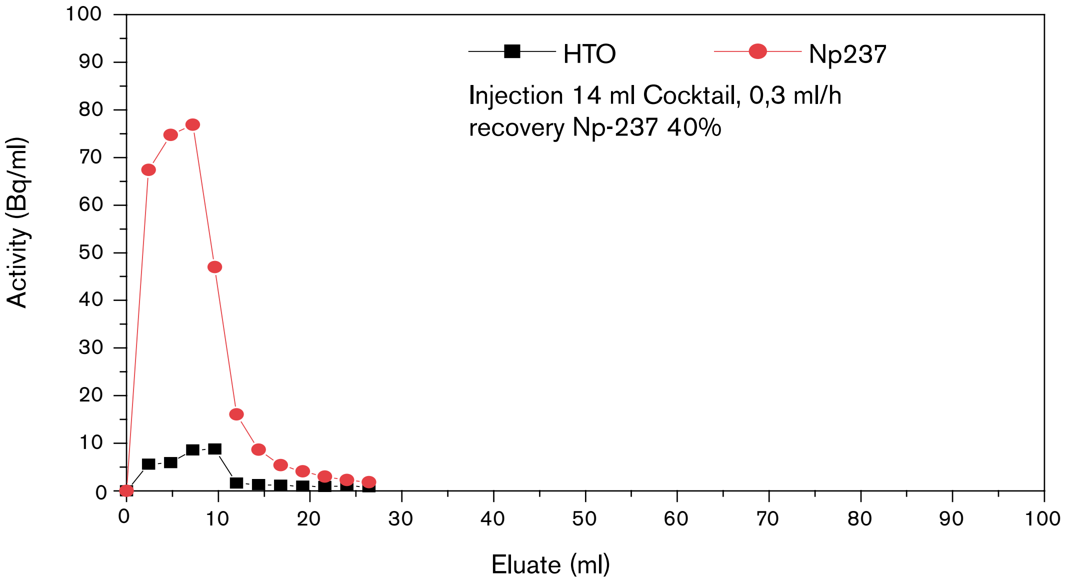


Figure 6-28. *Breakthrough curves for tritiated water and total a concentration from the first in situ CHEMLAB actinide migration experiment.*

To determine the profiles of the sorbed actinides along the fractures of the drill core, the fracture will be conserved by epoxy resin, cut in slices and analyzed chemically as well as by laser ablation techniques. These techniques are under preparation at present.

TUC concluded the investigations addressing 1) mobilization and immobilization of selected trace elements in different granitic rocks and fluids and 2) mobilization behaviour of Uranium and Thorium as a natural analogue for the mobility of actinides in granitic rocks. Final Reports will be issued in 2001.

A new project was started by TUC in which the mobility of short-lived U-238 decay products (U-234 and Th-230) in alterated fracture fillings in the past is used as a natural analogon for assessing actinide migration in the future. The investigations are based on the following idea: Within the Äspö-granitoids, secondary calcites occur as some million years old fracture-fillings. U is fixed in these calcites in low concentrations (usually <10 ppm) and it is assumed to have been in or close to secular equilibrium with its short-lived decay products. Upon reaction between migrating solutions and calcites, U can specifically be taken up by the secondary calcites or, alternatively, can partly be extracted from the calcites, whereas Th is assumed to be generally insoluble. The interpretation of the activity ratios in calcite fracture fillings is based on a model of old (more than 1 million years) calcites which have been disturbed by U-234-gain or -loss after a previous state of secular equilibrium in which the activity ratios were $^{234}U/^{238}U=1$ and $^{230}Th/^{234}U=1$. From the activity ratios of $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ in the calcites it can be determined whether U-234 gain or loss occurred and the time can be assessed at which the disturbance of the secular equlibrium occurred.

6.2.5 GRS

GRS will conduct electrical resistivity measurements in the Prototype Repository Project in boreholes and backfilled tunnel sections. The aim is to investigate time-dependent changes of water content in the buffer, the backfill, and in the EDZ. In these investigations advantage is taken of the dependence of the electrical resistivity in rocks on water content, porosity, and pore fluid resistivity. In order to correlate the measured resistivity with the water content, the field measurements will be accompanied by laboratory tests.

In the year 2000, in cooperation with SKB the measuring programme was finalized. The programme includes the installation of two electrode rings in the backfilled drift above the deposition boreholes, four electrode chains at the top of deposition borehole #5 and three electrode chains between deposition boreholes #5 and #6 (Figure 6-29).

Special pressure-watertight cables and connectors have been ordered for connecting the electrodes to the geoelectrical measuring system which will be installed in the parallel running G-tunnel.

Laboratory tests have been started aimed at providing relations between resistivity and solution content of granite, buffer, and backfill. These relations are needed for interpretation of the resistivity data in terms of water or solution content, respectively. Results are already available for granitic rock from earlier investigations. The results of the buffer tests obtained so far indicate most significant resistivity changes between water contents of 11 and 16 wt %. At higher water contents only comparatively small changes were measured. Calibration measurements on the backfill material will be performed during the coming months.

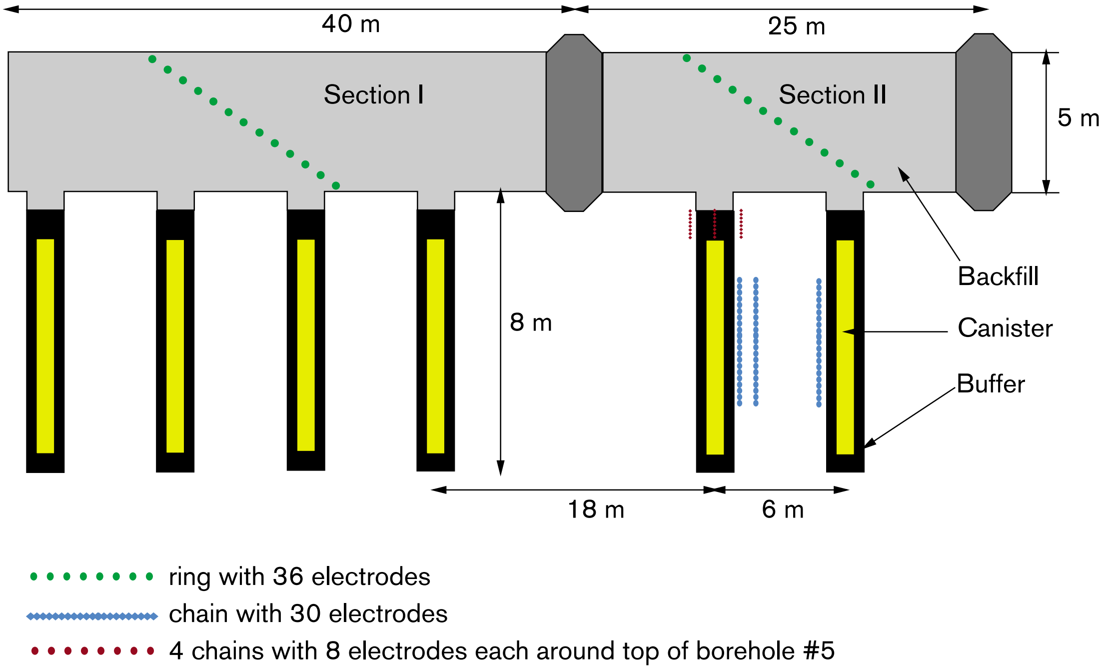


Figure 6-29. *Arrangement of electrodes in the Prototype Repository.*

Percolation of one sample of compacted bentonite is being continued. At present a total of about 180 g solution has percolated the sample which corresponds to about 60 times the initial pore volume. During the entire experiment, sulfate was released from the sample which may be accounted for by the oxidation of pyrite. The concentrations of Mg and Ca exceed those of the initial solution (Figure 6-30 and Figure 6-31). This finding can be interpreted as a result of two coupled processes: (i) dissolution of accessories in MX-80 and (ii) cation exchange. In the initial phase, Mg and Ca is taken up by cation exchange, and therefore the respective concentrations decrease. On the other hand, Mg and Ca release exceeds their decrease due to cation exchange and their concentration is increasing. We expect a plateau after some time which would indicate a state of stationary equlibrium between inflowing solution and mineral dissolution.

The observed solution compositions do not indicate significant changes in pore fluid resistivity during migration of formation water through the buffer material. Therefore, interpretation of the in situ measured resistivity data will be easier. However, this statement needs still to be confirmed by separate conductivity measurements in artificially prepared solutions with compositions similar to those observed during the percolation experiment.

Since resistivity measurements will be performed in the surroundings of the heated deposition boreholes at elevated temperatures, alteration of the formation water conductivity is determined in the temperature range between 15 and 70°C. An increase of electrical conductivity with increasing temperature is expected which may affect the measurement results especially in the buffer where only small resistivity changes will occur.

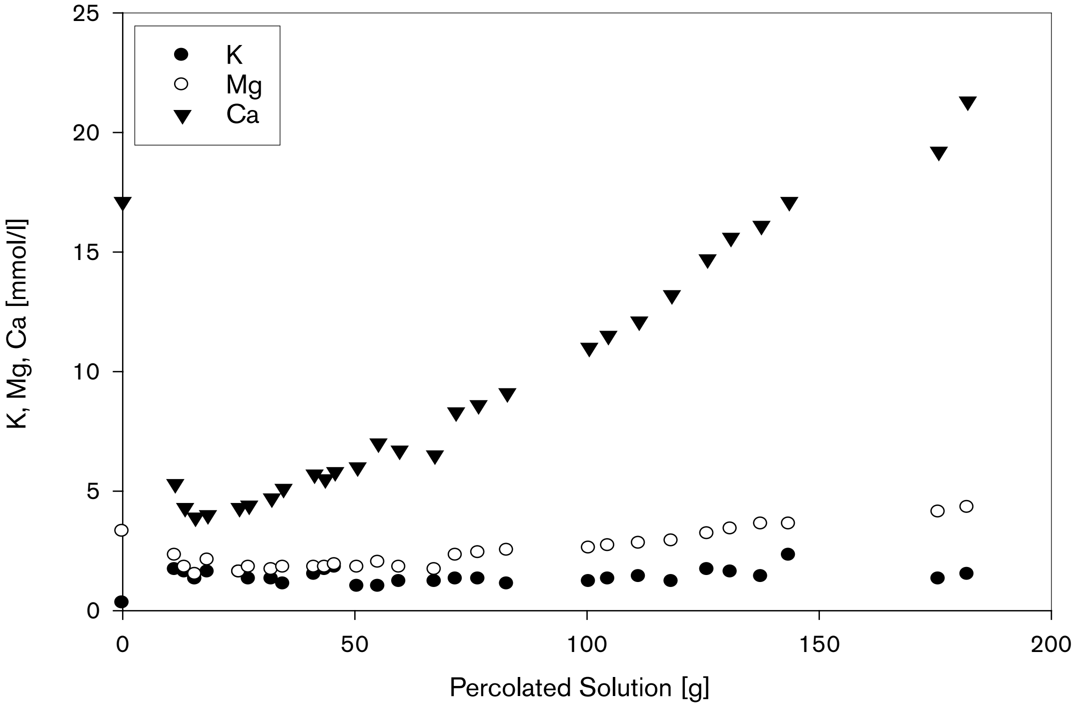


Figure 6-30. *K, Mg, and Ca-concentration during the percolation experiment.*

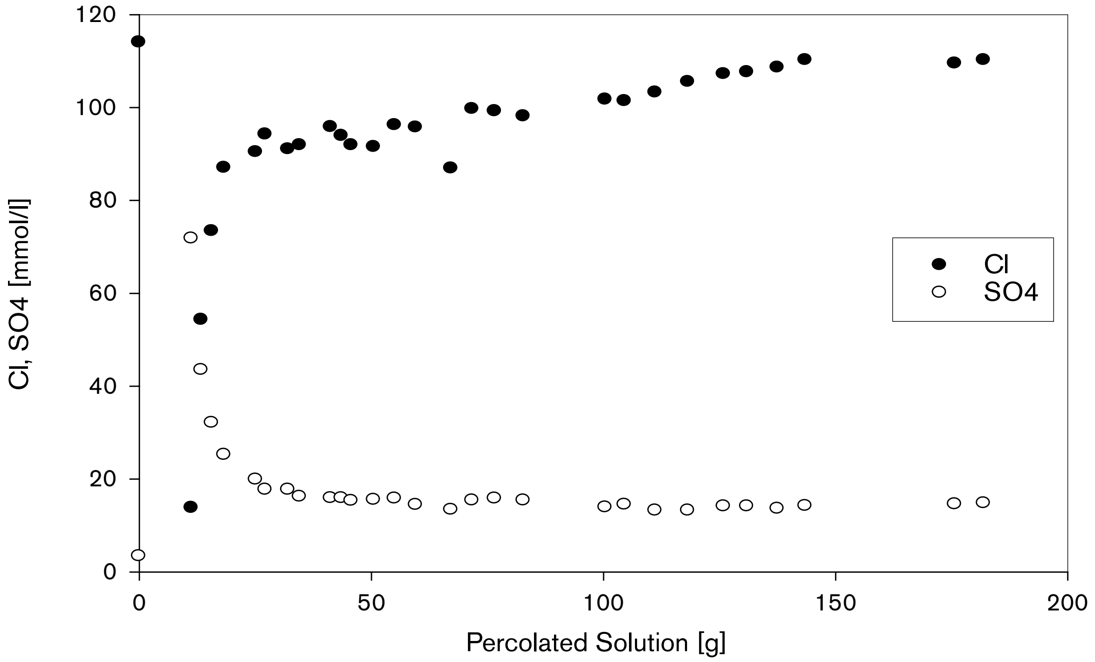


Figure 6-31. Cl and SO4-concentration during the percolation experiment (Cl-concentrations were calculated from electrical balancing).

6.2.6 USDOE/Sandia

The working agreement between Sandia National Laboratories and SKB in support of the contract to SKB from the U.S. 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 visualization 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. Work on all three of these tasks was conducted in calendar year 2000. A summary of the work conducted on each task is provided below.

Sandia National Laboratories joined the Äspö task force in September of 1998 in order to be involved with the TRUE-1 tracer test planning and evaluation. Sandia National Laboratories hosted the February, 2000 Äspö Task Force meeting in Carlsbad, New Mexico from the 7th to the 11th. A total of 35 participants from 8 different countries attended the meetings. In addition to the technical presentations on Tasks 4 and 5, highlights of the meetings included a tour of Carlsbad Caverns and an underground tour of the WIPP site. The second task force meeting of 2000 was held in Säro, Sweden in November and was attended by Sean A. McKenna from SNL.

Task 1

The objective of Task 1 is to validate the multirate mass-transport model developed at WIPP in a vastly different geologic environment. Previous work on Task 1 was comprised of the estimation of the STT-1 and STT-1b tracer tests from the TRUE-1 programme. These estimations provided familiarity with the TRUE-1 data and experience with using the multirate model to estimate those data. Prior to 2000, a blind prediction of the STT-2 data was also made. In 2000, estimation of the STT-2 data was the primary goal of Task 1. Preliminary estimation of these data were presented at the Äspö Task Force meeting held in Carlsbad, New Mexico in February. The STT-2 data are significantly different than the STT-1 and STT-1b data in that two separate transport pathways are evident in the breakthrough curve data. The preliminary estimates of the STT-2 data presented in Carlsbad used a single pathway model to try and represent the observed breakthrough curves. After the Äspö task force meeting, additional work was done to develop a two-path estimation procedure. Results of this two-path estimation procedure were presented at the American Geophysical Union, Western Pacific Geophysical meeting in June in Tokyo, Japan. Figure 6-32, shows results of this two-path estimation procedure.

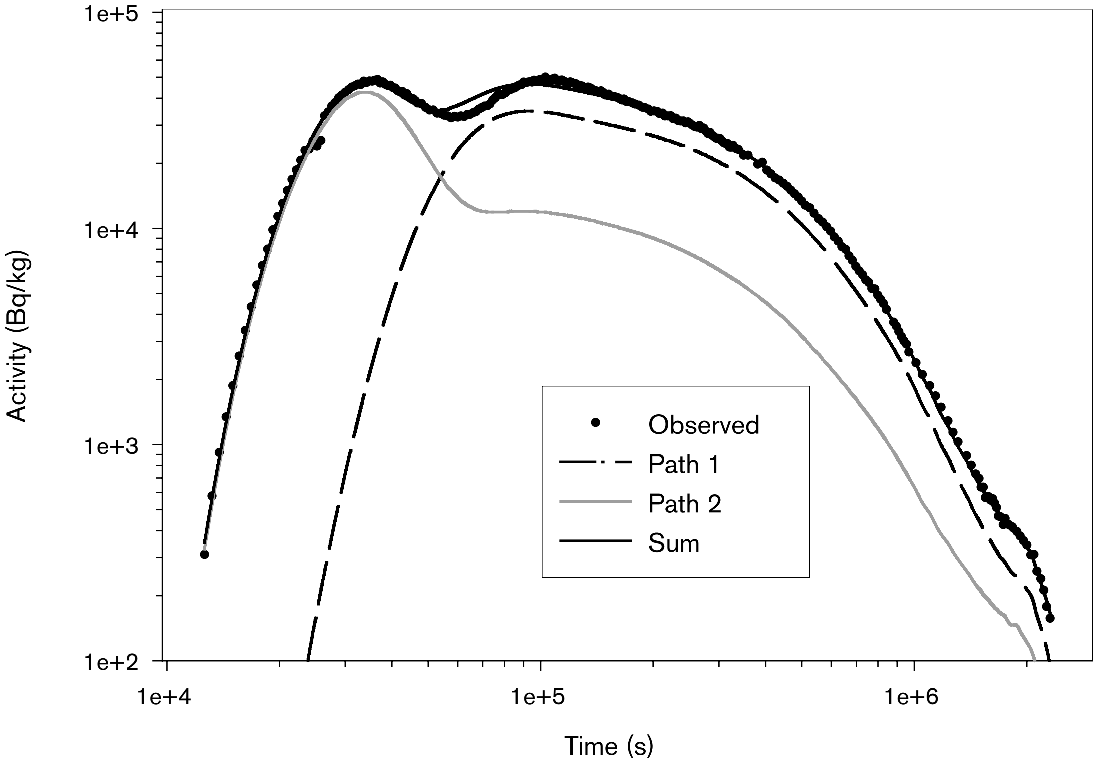


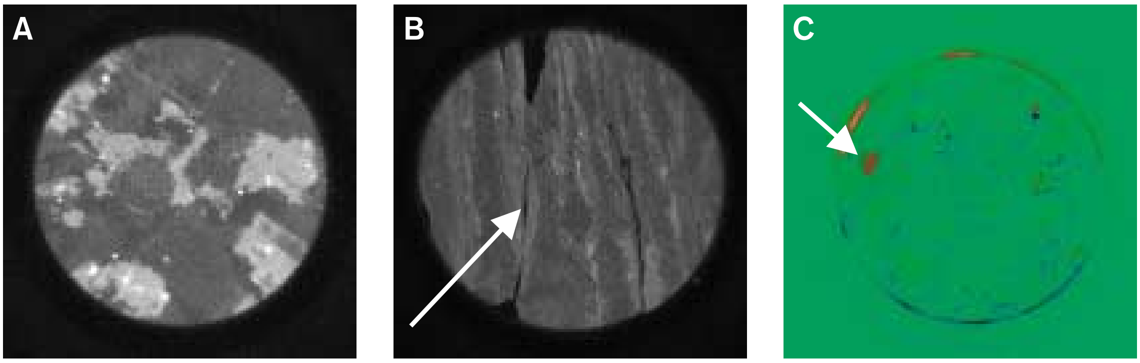
Figure 6-32. *Double transport pathway model fit to the HTO data from tracer test STT-2. The final fit to the data is the sum of the two different pathways.*

Task 2

The objective of Task 2 is to develop new techniques for the visualization of mass-transfer processes in low porosity rock. In 2000, visualization of mass-transfer processes in the Äspö diortie was focussed on determining the potential of X-ray micro-tomography as an imaging tool. Preliminary testing was done to determine the viability of micro-tomographic analysis of approximately 1cm diameter rock cores. X-ray beam intensity was varied to observe differences in contrast between two tracers: potasium iodide (KI) and cesium (Cs).

Four different X-ray intensities were used to look at tracer behavior below and above the potassium iodide and cesium absorption edges. An absorption edge is the energy level at which X-ray absorption reaches a maximum for a particular element or compound. The lower energy boundary tends to be quite sharp while above this boundary the boundary absorption decreases more slowly with increasing x-ray energy. We sought to maximize the visibility of the tracer, with higher absorption, while maintaining detail within the rock matrix. Experimentally determined edges were 33.675 KeV and 36.55 Kev for KI and Cs, respectively. Micor-tomographic scans of a single rock core at energies of 33.65 KeV, 33.69 Kev, 36.53 KeV, and 36.59 KeV were used to bracket the absorption edge.

Preliminary inspection of the data found we were not getting adequate x-ray transmission through the rock cores in zones containing fault gouge, a region of interest for observing liquid transport. So we increased the beam energy. Initial results suggest that a beam energy of 45 KeV, above the Cs absorption edge, produced better image data overall. The higher energy provided good contrast in undisturbed native rock while maximizing the signal to noise ratio in the fault gouge. This also suggests Cs would be better than KI as a tracer, providing more beam attenuation.



Granodiorite from Kamaishi Mine, Japan

Sheer-zone material from Grimsel test site, Switzerland

Diorite from Äspö Underground Laboratory, Sweden

Figure 6-33. *Two-dimensional slices taken from three-dimensional images obtained nondestructively using synchrotron source microtomography at the Advanced Photon Source at Argonne National Laboratory. The images demonstrate how the technique can be used to A) differentiate mafic from felsic minerals, B) visualize and be used to quantify pore space, and C) focus on different tracers and how tracers can be used to enhance the visualization of pore space.*

Task 3

Work on Task 3 in 2000 was focussed on the comparison of performance assessment scale transport calculations done at SKB using the FARF-31 transport code and transport calculations over the same scale done with the multirate transport code, STAMMT-L, developed at Sandia National Laboratories for use on the WIPP project. For both codes, parameters estimated from the STT-1 tracer tests (Task 1) are used as the basis for comparison. Comparison of the results is ongoing at this time and is focussed on the differences in how the two different models represent the diffusive capacity within the rock. TheFARF-31 results demonstrate infinite diffusive capacity, even at PA time scales, while the STAMMT-L results show a large fraction of the capacity coming to equilibrium with the fracture concentrations. Results of an initial comparison between the two models are shown in Figure 6-34.

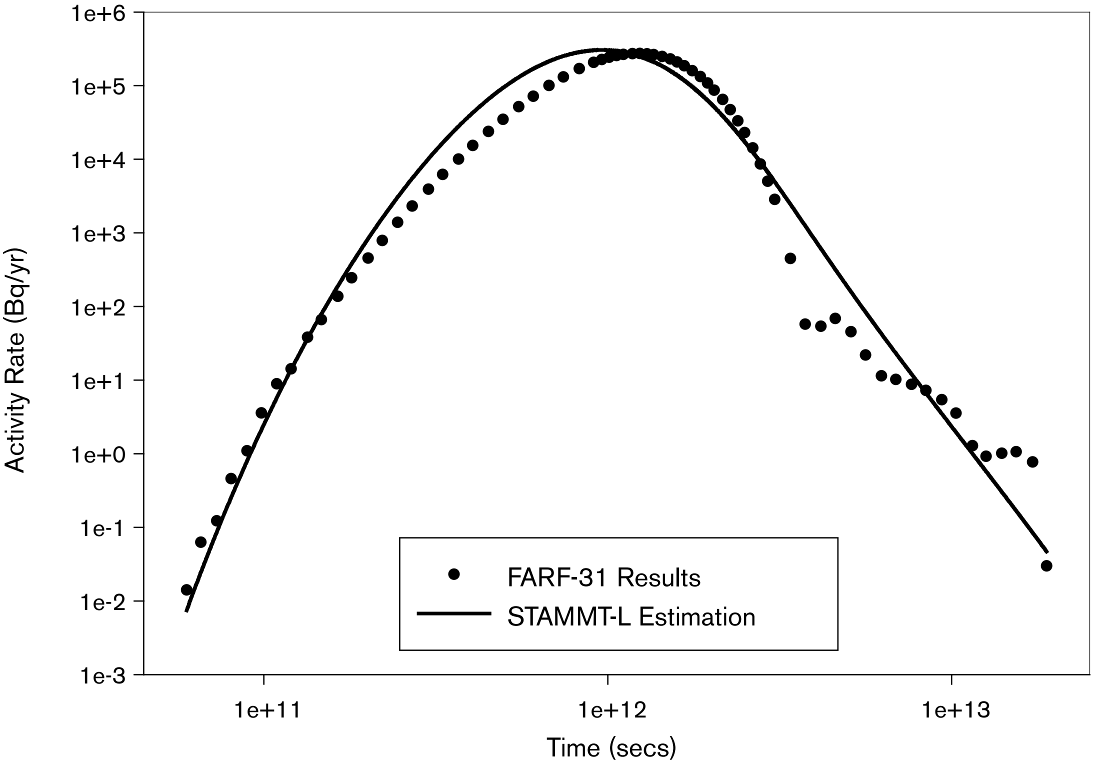


Figure 6-34. *Estimation of the Single-Rate FARF-31 performance assessment results using the multirate model STAMMT-L.*

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