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Äspö Hard Rock Laboratory

Annual Report 2002

Svensk Kärnbränslehantering AB

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Abstract

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

One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The Äspö HRL was opened in 1994 as a research centre and underground laboratory. The associated research, development, and demonstration tasks, which are managed by the Repository Technology Unit within SKB, have so far attracted considerable international interest.

Natural Barriers

The bedrock with available fractures and fracture zones, its properties and on-going physical, chemical and biological processes, which affect the integrity of the engineered barriers and the transport of radionuclides, are denoted the natural barriers of the deep repository. The experiments performed in Äspö HRL are related to the rock, its properties, and *in situ* environmental conditions. The strategy for the on-going experiments is to concentrate the efforts on those experiments that are of importance for the site investigations. Tests of models for groundwater flow, radionuclide migration and chemical/biological processes are one of the main purposes of the Äspö HRL. The programme includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to conceptual and numerical models. Ongoing projects are Tracer Retention Understanding Experiments, Long Term Diffusion Experiment, Radionuclide Retention Experiments, Colloid Project, Microbial Project, Matrix Fluid Chemistry, Modelling of Groundwater Flow and Transport of Solutes and PADAMOT.

The retardation in rock is studied at different experiment scales in a programme called *Tracer Retention Understanding Experiments* (TRUE). The overall objectives of the experiments are to increase the understanding of the processes, which govern retention of radionuclides transported in crystalline rock, and to increase the credibility in models used for radionuclide transport calculations. During 2002, work has been performed within three sub-projects; TRUE Block Scale, TRUE Block Scale Continuation and TRUE-1 continuation. Concluding activities have been performed in the TRUE Block Scale project. This includes drawing major conclusions from the concluding reports dealing with transport modelling and synthesis of results and achievements. In the TRUE Block Scale Continuation project the main activities have been complementary monitoring, sampling, and analyses of the breakthroughs of the Phase C tracer injections. The continued sampling and analyses have enabled improved description of the tail of the breakthroughs. In addition, a comprehensive groundwater sampling campaign was conducted in the TRUE Block Scale borehole array in December 2002. The results are e.g. expected to provide additional information which can help condition the hydro-structural model for the TRUE Block Scale rock volume. In the TRUE-1 continuation project mainly complementary *in situ* tests, radon measurements for fracture aperture determinations, and work to identify candidate fault rock zones for future rock characterisation experiments have been performed.

The *Long Term Diffusion Experiment* constitutes a complement to performed diffusion and sorption laboratory experiments, and is a natural extension of the experiments conducted as part of the TRUE experiments. The difference is that the longer duration (3–4 years) of the experiment is expected to enable an improved understanding of diffusion and sorption in the vicinity of a natural fracture surface. The experiment will be performed in a core stub with a natural fracture surface isolated in the bottom of a large diameter telescoped borehole. The borehole experimental set-up was installed late 2002. Subsequently various tests and groundwater sampling for chemical and microbe analyses have been collected. During 2002 a number of problem areas were defined e.g. the excavation work at two sites in Äspö HRL during 2003 is expected to produce hydrological interference at the LTDE site, precautions must be taken to avoid build-up of bacteria and formation of bio-films, and the instrumentation of the borehole is complicated and therefore a test programme has been initiated. The experiments at the site will start when the excavation work is completed and more stable conditions are achieved in Äspö HRL.

Radionuclide retention experiments are carried out with the aim to confirm result from laboratory experiments *in situ*, where conditions representative for the properties of groundwater at repository depth prevail. The experiments are carried out in CHEMLAB 1 and CHEMLAB 2 that are special borehole probes. In CHEMLAB 1 two kinds of experiments to study the influence of radiolysis on the mobility of technetium in bentonite were started in the end of 2002. In the indirect radiation experiments, the water is irradiated before it comes in contact with the cell containing bentonite and reduced technetium and in the direct radiation experiment, the irradiation source is placed in the experiment cell, close to the technetium, and thereby the radicals produced will play a role. Experiments to study migration of actinides in natural fractures in drillcores are being carried out in CHEMLAB 2. The second of several actinide migration experiments was performed during fall 2001 until February 2002. These results together with those of preliminary laboratory investigations with the same type of cores were presented in the MRS 2002 Conference. The third actinide experiment was started at the end of 2002 and is still under completion due to several technical problems with CHEMLAB 2.

The findings of potential transport of solutes by colloids and access to more sensitive instruments for colloid measurements motivated a *Colloid Project* at Äspö HRL. The project comprises studies of the stability and mobility of colloids, measurements of the colloid concentration in the groundwater at Äspö, bentonite clay as a source for colloid generation, and the potential of colloids to enhance radionuclide transport. During 2002 the natural background colloid concentrations were measured at Äspö HRL. The major finding from the background colloid measurements is that, despite different techniques and sometimes large uncertainties in the measurements, the colloid content at repository depth is in the order of ppb. These results support earlier measurements and modelling. Borehole specific measurements to determine the colloid generation properties of bentonite clay in contact with groundwater are planned and during 2002 laboratory tests concerning the design and optimisation of the colloid reactors were made.

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future deep repository for spent fuel. There are presently four specific microbial process areas identified that are of importance for proper repository functions and that are studied in the *Microbe Project*. The process areas are; bio-mobilisation of radionuclides, bio-immobilisation of radionuclides, microbial effects on the chemical stability, and microbial corrosion of copper. The conditions under which Biological Iron Oxides Systems develop have been studied at two sites. The results clearly demonstrated the strong advantage with artificial channels versus a natural ditch in the tunnel for future studies of bio-mobilisation of radionuclides. The work in the area of microbial effects on the chemical stability has focussed on the set up of a well equipped laboratory container. The laboratory has a climate control system, analytical instrumentation, and an anaerobic box for work with oxygen sensitive organisms and trace elements. Microbial induced copper corrosion by hydrogen sulphide, produced by sulphate reducing bacteria (SRB), has been studied. These investigations were performed under *in situ* conditions on copper plates installed in bentonite compacted to different densities. It was found that SRB were active and produced hydrogen sulphide during the initial phase of bentonite swelling and the activity of the SRB could be correlated with the final density of the bentonite. It was also demonstrated that SRB are present in a dormant state in the commercial MX-80 bentonite and these dormant SRB become activated by addition of water.

The main objectives of the *Matrix Fluid Chemistry* experiment are to understand the origin and age of matrix fluids, i.e. accessible pore water, in fissures and small-scale fractures and their possible influence on fluid chemistry in the bedrock. The project comprise a feasibility study carried out on drill core material, leaching and permeability experiments including crush/leach experiments, and a full-scale programme designed to sample and analyse matrix fluids from isolated borehole sections. The first phase of the project increased the knowledge of matrix pore space fluids/groundwaters from crystalline rocks of low hydraulic conductivity, and this complemented the hydrogeochemical studies already conducted at Äspö. The first phase of the project was finalised during 2002 and will be reported during 2003.

An important goal for the activities at Äspö HRL includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models. An important part of this work is performed in the international co-operation *Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*. The work in the Task Force is closely tied to ongoing and planned experiments at the Äspö HRL. Specified tasks are defined where several modelling groups work on the same set of field data. The modelling results are then compared to the experimental outcome and evaluated. The Tasks 1–3 are already completed. The TRUE-1 experiments form the base for the modelling in Task 4 and the overall evaluation is near to be completed and reported. The modelling exercises in Task 5 have been completed. Based on the modelling team reports, work was made to compile results and summarise approaches, executions, and conclusions of Task 5 into one summary report. In addition, an evaluation of the task was initiated and performed by external reviewers. Task 6 was initiated in 2001 and comprises modelling work on selected TRUE-1 tests with performance assessment models and site characterisation models. During 2002, work on modelling reports has been made and the results were presented at the 16th Task Force Meeting at Äspö HRL in June 2002. The work to construct a 50–100 m block scale synthesised structural model using data from the Prototype Repository, TRUE Block Scale, TRUE-1, and FCC (Fracture Characterisation and Classification) was near to be complete in 2002. The developed model will be used as input to future modelling tasks.

Palaeohydrogeology is a relatively new term used as a common name for information from fracture minerals that is used for interpretations of past hydrogeochemical and hydrogeological systems. When the EC-project EQUIP, which concentrated on the formulation of a methodology for how to conduct a palaeohydrogeological study, ended in 2000 there was a need for continued fracture mineral investigations and model testing of the obtained results and a new EC-project was initiated in the beginning of 2002. This project is called *PADAMOT* (Palaeohydrogeological Data Analysis and Model

Testing) and includes further developments of analytical techniques and modelling tools to interpret data, but also further research to investigate specific processes that might link climate and groundwater properties in low permeability rocks. During 2002 the work has continued with sample preparation and analyses of drill core samples from the deep borehole KLX01 located at Laxemar on the mainland west of Äspö. The basic idea behind the sampling/analysis programme is to distinguish and characterise possible recent low temperature calcites. The samples reflect a relatively deep influx of meteoric water and past melt water. In 2–3th October a workshop organised by the PADAMOT co-ordinator was held in Brussels.

Disposal technology

The Äspö HRL makes it possible to demonstrate and perform full-scale tests of the function of different components of the repository system. It is also important to show that high quality can be achieved in design, construction, and operation of the repository. To fulfil these tasks several projects are performed, e.g. Demonstration of Repository Technology, Prototype Repository, Backfill and Plug Test, Canister Retrieval Test, Long Term Tests of Buffer Material, Pillar Stability Experiment, Low-pH cementitious products, KBS-3 method with horizontal emplacement and Cleaning and sealing of investigation boreholes.

The project *Demonstration of repository technology* provides a full-scale demonstration of canister deposition under radiation-shielded conditions and works with testing of canister and bentonite handling in full size deposition holes. Testing and demonstration of the deposition process is going on, e.g. in the Prototype Repository.

The *Prototype Repository* project focuses on testing and demonstrating repository system function in full scale and is co-funded by the European Commission. The experiment comprises six full size canisters with electrical heaters surrounded by bentonite. The inner section (Section I) with 4 canisters was completed during 2001. The original plan was to continue the installation of the outer section (Section II) during 2002. But, the heaters in the Canister Retrieval Test exhibited a malfunction late 2001, and since the construction of these heaters were the same as the heaters in the Prototype Repository it was deemed needed to understand the cause of the malfunction before the canisters of Section II were installed. During the autumn of 2002 it became evident that pyrolysis of the insulation material around cables and the lay-out of the lead-throughs were the major causes to the problems. Based on these findings a new design of the lead-throughs was developed and constructed. It was also concluded that no specific action was deemed necessary to be taken in order to improve the operating conditions for the 4 installed canisters. A large number of sensors are installed in the buffer, backfill and surrounding rock. A general conclusion after about 1.5 years of operation is that the measuring system and transducers works well. In addition to the installation and measurements during operation other ongoing activities are e.g. conceptual modelling and model development. According to present plans the outer section will be installed during 2003.

The *Backfill and Plug Test* is a test of the hydraulic and mechanical function of different backfill materials, emplacement methods, and a full-scale plug. The 28 m long test region is located in the ZEDEX drift. The inner part of the drift is backfilled with a mixture of bentonite and crushed rock and the outer part is filled with crushed rock. The test region is divided into sections by permeable mats, which are used for artificial addition of water to the backfill. The wetting of the backfill started late 1999 and the final step of increasing the water pressure in the mats to 500 kPa was taken in January 2002. The water saturation, water pressure, and swelling pressure in the backfill is continuously measured and recorded and at the end of 2002 the moisture measurements indicated that the entire backfill seems to be completely water saturated. The flow testing can therefore start during 2003 as planned.

The *Canister Retrieval Test*, located in the main test area at the 420 m level, is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite is fully saturated. Bentonite blocks, bentonite pellets, and canisters with heaters have been implemented in one vertically bored test deposition hole in full repository scale. Artificial addition of water is provided regularly around the bentonite blocks and the test has been running for a little more than two years with continuous measurement of the wetting process, temperature, stresses and strains. There is a defect in the heaters (see "Prototype Repository" above) causing a low resistance to earth which remain, but the heaters have worked properly and a steady, but slightly reduced, power has been maintained and it has been decided to continue the test. Large number of parameters is measured during the test to provide a basis for modelling purposes. The relative humidity sensors indicate that the bentonite between the rock and the canister is close to water saturation although the wetting seems to be somewhat uneven.

The *Long Term Test of Buffer Material* 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 at conditions similar to those in a KBS-3 repository. The testing principle is to emplace "parcels" containing heater, central copper tube, pre-compacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m. At termination of the tests, the parcels are extracted. The water distribution in the clay is determined and subsequent well-defined chemical and mineralogical analyses as well as physical tests are performed. One parcel was extracted late 2001 and the bentonite material, the in bentonite incorporated copper coupons and tracers have been analysed during 2002 and the results are presently being reported. The remaining four parcels have functioned well and water pressure, total pressure, temperature, and moisture content have been continuously measured.

A *Pillar Stability Experiment* has been initiated at Äspö HRL to complement an earlier study performed at URL in Canada. The major aims are to demonstrate the capability to predict spalling in fractured rock mass and the effect of the buffer on the propagation of micro cracks. During 2002, numerical predictive modelling of the experiment has been performed and based on geological and hydrogeological information from four characterisation boreholes a preferential site has been selected.

A project with the aim to qualify the use of *Low-pH cementitious products* (leachates below pH 11) for applications like structural cast concrete, shotcrete, rock bolting, and grouting in a repository is carried out by SKB, Posiva, and NUMO in co-operation. Work with the repository performance has established that a pH below 11 in the pore water can be accepted to assure the long-term repository performance and safety. It was, however, found more difficult than expected to find suitable injection grouts that penetrate fine fractures and a planned small field test has therefore been postponed. The present focus is put on finding suitable recipes for injection grouts. Thereafter, when suitable low-pH recipes have been developed, small field tests in Äspö HRL are planned to take place where both grouting and rock bolting will be tested.

Late 2001 SKB published an R&D-programme for the *KBS-3 method with horizontal emplacement* (KBS-3H). The programme, which is carried through by SKB and Posiva in co-operation, was divided into four parts: Feasibility Study, Basic Design, Construction and Testing at the Äspö HRL, and Evaluation. The Feasibility Study finalised in

October 2002 showed that the KBS-3H method is worth further development from a technical, economical, and long-term safety point of view. During 2002 a barrier performance safety assessment, describing the differences between horizontal and vertical emplacement with respect to buffer behaviour, was also performed.

In the project *Cleaning and sealing of investigation boreholes* the best available techniques for this are to be identified and demonstrated. Investigation boreholes are drilled during site investigations and detailed characterisation in order to obtain data on the properties of the rock. These boreholes must be cleaned and sealed, no later than at the closure of the deep repository. Cleaning of the boreholes means that instrumentation that has been used in the boreholes during long time periods, in a sometimes aggressive environment, is removed. Sealing of the boreholes means that the conductivity in the borehole is no higher than that of the surrounding rock. A state of the art report summarising the developments of the techniques during the last 10–15 years has been put together.

Äspö facility

The main goal for the operation of the Äspö facility is to provide a safe and environmentally correct facility for everybody working or visiting it. During 2002 the operation of the facility has worked smoothly and the reliability of service in the facility and the underground-related systems has been almost 98%. A new storage facility, for underground equipment, was taken in use during the spring. The construction work for new office space started in September 2002 and will be finalised during spring 2003. The rock and reinforcement programme has continued and work on increased fire safety underground has included an extension of the water distribution system.

The main goal for the information group is to create public acceptance for SKB's activities in co-operation with other departments at SKB. This is achieved by presenting information about SKB, the ongoing site investigations and the three facilities in operation in the municipality of Oskarshamn (Äspö HRL, CLAB and the Canister Laboratory). During 2002, Äspö HRL and the site investigations at Simpevarp had 10 000 visitors and the total amount of visitors to all facilities in Oskarshamn was 15 000 persons.

An important part of the activities at the Äspö facility is the administration, operation, and maintenance of instruments as well as development of investigation methods. The monitoring of groundwater head, flow, and chemistry at Äspö calls for efficient data collection system and data management procedures. This is handled by the Hydro Monitoring System (HMS) for on-line recording.

International co-operation

Eight organisations from seven countries participated in the co-operation at Äspö HRL during 2002. Most of the organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several of the organisations are participating in the experimental work as well as in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.

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

Environmental research

The experiments performed in Äspö HRL are not exclusively focused on radionuclide related processes but also on non-radioactive environmental issues. Äspö Environmental Research Foundation was founded 1996 on initiative of local and regional interested parties, with the aim to make the underground laboratory available for environmental research.

In an agreement with the foundation and the Geological Survey of Sweden (SGU) field experiments started in 2001 at Äspö HRL to investigate the retention and degradation of petroleum products at *in situ* conditions.

The University of Kalmar founded during 2002 the Äspö Research School on the initiative of the Äspö Environmental Research Foundation. The objective is to provide conditions for today's and tomorrow's research concerning environmental issues at the school.

Sammanfattning

Äspölaboratoriet är en viktig del i SKB:s arbete med utformning, byggande och drift av ett djupförvar för använt kärnbränsle samt för utveckling och testning av metoder för karakterisering av en lämplig plats för ett djupförvar.

Ett av de grundläggande skälen till SKB:s beslut att anlägga ett underjordslaboratorium var att skapa förutsättningar för forskning, utveckling och demonstration i en realistisk och ostörd bergmiljö på förvarsdjup. Underjordslaboratoriet och forskningscentret på Äspö invigdes 1994. Äspölaboratoriet och verksamheten som bedrivs där, av avdelningen Förvarsteknik inom SKB, har hittills väckt stort internationellt intresse.

Naturliga barriärer

Berget med dess sprickor och sprickzoner, dess egenskaper samt pågående fysikaliska, kemiska och biologiska processer, vilka påverkar ingenjörsbarriärernas egenskaper och radionuklidtransporten, benämns djupförvarets naturliga barriärer. Experimenten som genomförs i Äspölaboratoriet vid *in situ* förhållanden kopplar till berget och dess egenskaper. Strategin för de pågående experimenten är att i huvudsak satsa på de experiment som är av stor vikt för platsundersökningarna. Ett viktigt syfte med verksamheten vid Äspölaboratoriet är att testa beräkningsmodeller för grundvattenströmning, radionuklidtransport och kemiska/biologiska processer. I programmet för testning av modeller ingår att utvärdera användbarheten av och tillförlitligheten hos de olika modellerna samt att utveckla och testa metoder för att bestämma de parametrar som krävs som indata till konceptuella och numeriska modeller. Pågående projekt är: ”Tracer Retention Understanding Experiments”, ”Long Term Diffusion Experiment”, ”Radionuclide Retention Experiments”, ”Colloid Project”, ”Microbial Project”, ”Matrix Fluid Chemistry”, ”Modelling of Groundwater Flow and Transport of Solutes” samt ”PADAMOT”.

Bergets förmåga att fördröja transporten studeras i olika experimentskalor i spårämnesförsöksprogrammet *”Tracer Retention Understanding Experiments* (TRUE)”. Syftet är att öka förståelsen för de processer som styr fördröjningen av radionuklider i granitiskt berg samt att öka tillförlitligheten hos de modeller som används för beräkning av radionuklidtransporten. Under 2002 har arbete bedrivits inom tre delprojekt: *”TRUE Block Scale”*, *”TRUE Block Scale Continuation”* och *”TRUE-1 Continuation”*. Delprojektet *”TRUE Block Scale”* har avslutats under året. Det avslutande arbetet har omfattat att formulera slutsatserna till sammanfattningsrapporterna som behandlar transportmodellering respektive resultat och landvinningar inom projektet. I *”TRUE Block Scale Continuation”* har kompletterande mätningar, provtagning och analys av erhållna genombrottskurvor från injekteringen av spårämnen i fas C genomförts. De kompletterande mätningarna och analyserna har möjliggjort en förbättrad beskrivning av genombrottskurvorna. Dessutom genomfördes en omfattande provtagning av grundvattnet i borrhålen i december 2002. Analyserna av den provtagningen förväntas bland annat ge ytterligare information till anpassningen av den hydrostrukturella modellen för den aktuella bergvolymen. Inom *”TRUE-1 Continuation”* har följande aktiviteter pågått: kompletterande *in situ* försök, radonmätningar för att uppskatta sprickvidd samt aktiviteter för att identifiera en lämplig sprickzon för de planerade bergkarakteriseringsexperimenten.

”*Long Term Diffusion Experiment*” är ett komplement till de sorptions- och spårämnesförsök som genomförts i laboratorium, det är också en utvidgning av de experiment som genomförts inom TRUE-programmet. Experimentet genomförs under lång tid (3–4 år) och förväntas ge en förbättrad förståelse av diffusion och sorption på och i närheten av naturliga sprickytor. Experimentet genomförs i en borrhålskärna i botten av ett teleskopformat borrhål. Borrhålskärnan har en naturlig sprickyta. Experimentutrustningen i borrhålet installerades i slutet av 2002. Därefter genomfördes olika tester och grundvattenprov togs för kemisk- och mikrobiellanalys. Under 2002 identifierades ett antal problemområden som måste beaktas: utbyggnaden av tunnelsystemet i Äspölaboratoriet under 2003 förväntas orsaka hydrologiska störningar vid försöksplatsen för LTDE, försiktighetsåtgärder måste vidtas för att undvika en utveckling av bakterier och bildning av bio-film samt instrumenten som används i borrhålet är känsliga och komplicerade. För att vara säker på att instrumenten fungerar bra tas testprogram för dessa fram. Experimenten i borrhålet kommer att påbörjas först när utbyggnaden av tunnelsystemet har avslutats och förhållandena åter är stabila i Äspölaboratoriet.

Fördröjning av radionuklider studeras i ”*Radionuclide Retention Experiment*”. Syftet med experimenten är att bekräfta resultat från laboratorieexperiment som genomförts vid förhållanden som liknar de som råder på förvarsdjup. Experiment genomförs i specialutvecklade borrhålsutrusningar, CHEMLAB 1 och CHEMLAB 2. Två typer av experiment genomförs i CHEMLAB 1 för att studera hur radiolysprodukter påverkar rörligheten hos teknetium i bentonit. Experimenten påbörjades i slutet av 2002. I den ena typen av experiment bestrålas grundvatten innan det kommer i kontakt med bentoniten och reducerat teknetium i testcellen. I den andra typen av experiment är strålkällan placerad i testcellen och grundvattnet bestrålas i direkt anslutning till teknetium.
I det senare fallet kan de radikaler som bildas vid bestrålningen av grundvattnet att kunna få betydelse. Migration av aktinider i naturliga sprickor i borrkärnor studeras i CHEMLAB 2. Det andra av flera försök genomfördes under perioden hösten 2001 till februari 2002. Resultaten presenterades tillsammans med preliminära laboratorieförsök på 2002 års MRS-konferens. Det tredje aktinidförsöket startades i slutet av 2002 och pågår fortfarande på grund av tekniska problem med CHEMLAB 2.

Indikationer på att lösta ämnen kan transporteras med kolloider liksom tillgången på känsligare instrument för att mäta förekomsten av kolloider i grundvatten resulterade i ett ”*Colloid Project*” vid Äspölaboratoriet. Projektet omfattar studier av kolloiders stabilitet och rörlighet, mätning av kolloidkoncentrationen i grundvattnen på Äspö, studier av bentonitens betydelse som källa för bildandet av kolloider samt potentialen för transport av radionuklider med kolloider. Bakgrundshalten av kolloider i grundvattnen på Äspö mättes under 2002. Den huvudsakliga slutsatsen är att trots förnyad mätteknik och ibland stora osäkerheter i mätningarna är kolloidhalten på förvarsdjup låg, det vill säga i storleksordningen ppb. Dessa resultat överensstämmer med tidigare mätningar och modellering. Borrhålsspecifika mätningar för att studera bentonitlerans förmåga att bilda kolloider i kontakt med grundvatten planeras. Under 2002 har laboratorieexperiment genomförts för att ta fram och optimera utformningen av en bentonitkolloidreaktor.

Mikroorganismer samverkar med sin omgivning och kan i vissa fall ge stor påverkan på förhållandena där. Sådan samverkan kan ge betydande påverkan på funktionen hos ett framtida djupförvar för använt kärnbränsle. För närvarande studeras fyra mikrobiella processer som har identifierats som viktiga för förvarets funktion i ”*Microbe Project*”. Processerna är: bio-transport av radionuklider, bio-sorption av radionuklider, mikrobiella effekter på de kemiska förhållandena och bio-korrosion av koppar. Förhållanden för att mikroorganismer som orsakar biologisk oxidation av järn ska etableras studeras vid två försöksplatser i Äspölaboratoriet. Resultaten visar på stora fördelar med att använda konstgjorda diken i stället för naturliga vid studier av bio-transport av radionuklider.

Inför studierna av mikrobiella effekter på de kemiska förhållandena har en container med ett välutrustat laboratorium installerats. Laboratoriet är bland annat försett med klimatanläggning, analysinstrument och en handskbox för hantering av mikroorganismer och spårelement i syrefri miljö. Korrosion av koppar som orsakas av vätesulfid som produceras av sulfatreducerande bakterier studeras också. Undersökningarna genomförs på kopparplåtar som placeras i kompakterad bentonit med olika densitet. Studierna visar att bakterierna är aktiva och producerar vätesulfid under det initiala vattenmättnadsskedet samt att bakterieaktiviteten kan korreleras till bentonitens slutliga densitet. Experimenten visar också att de sulfatreducerande bakterierna förekommer i ett vilande tillstånd i kommersiell MX-80 bentonit och att de vilande bakterierna blir aktiva då vatten tillsätts.

Syftet med projektet *"Matrix Fluid Chemistry"* är att bestämma ursprung och ålder på matrisvatten, det vill säga tillgängligt porvatten i små sprickor, och dess inverkan på vattenkemin i berget. Projektet har omfattat en förstudie där laknings- och permeabilitetsexperiment på material från en borrkärna genomförts. Förstudien omfattar även lakförsök på krossat material. Fullskaleprogrammet har omfattat provtagning och analys av matrisvatten från en isolerad borrhålssektion. Genomförandet av den första fasen av projektet har givit ökad kunskap om matrisvattnet i kristallint berg med låg hydraulisk konduktivitet. Denna kunskap utgör ett viktigt komplement till tidigare hydrogeokemiska studier som genomförts vid Äspölaboratoriet. Den första fasen av projektet avslutades under 2002 och den kommer att avrapporteras under 2003.

Ett viktigt mål med aktiviteterna vid Äspölaboratoriet är att ta fram dataunderlag till de projekt som syftar till att utvärdera användbarheten och tillförlitligheten hos olika beräkningsmodeller samt att utveckla och testa metoder för att bestämma de parametrar som krävs som indata till modellerna. En viktig del av detta arbete genomförs i ett internationellt samarbetsprojekt *"Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes"*. Arbetet i projektet har anknytning till pågående och planerade experiment vid Äspölaboratoriet. Flera modelleringsgrupper arbetar med definierade uppgifter och använder samma fältdata. Modelleringsresultaten utvärderas och jämförs med data från experimenten. Tre arbetsuppgifter ("Tasks 1–3") har avslutats. TRUE-1 försöken utgör basen för modelleringsarbetet i "Task 4". Den övergripande utvärderingen och en rapport håller på att färdigställas. Modelleringen av "Task 5" har avslutats. Baserat på gruppernas delrapporter tas en sammanfattningsrapport som innehåller de huvudsakliga slutsatserna från "Task 5" fram. En extern granskningsgrupp genomför dessutom en utvärdering av "Task 5". "Task 6" omfattar modellering av utvalda delar av TRUE-1 försöket med de beräkningsmodeller som används för att göra säkerhetsanalyser respektive platskarakterisering. Under 2002 har grupperna arbetat med avrapporteringen av modelleringen och resultaten presenterades på det 16:e "Task Force"-mötet som hölls på Äspö i juni 2002. Arbetet med att ta fram en strukturmodell i blockskala (50–100 m) baserad på data från Prototypförvaret, TRUE Block Scale, TRUE-1, och FCC ("Fracture Characterisation and Classification") kunde nästan avslutas under 2002. Den framtagna modellen ska användas som indata till framtida modelleringsuppgifter.

Palaeohydrogeology är en relativt ny benämning som används för att beskriva den information om förflutna hydrogeokemiska och hydrogeologiska system som erhålls vid utvärdering av sprickfyllnadsmaterial. EU-projektet EQUIP syftade till att ta fram en metod för hur palaeohydrogeologiska studier ska genomföras. När detta projekt avslutades 2000 fanns ett behov av att fortsätta arbetet med att undersöka sprickmineraler samt att modellera erhållna resultat och därför initialiserades ett nytt EU-projekt i början av 2002. Projektet fick namnet *PADAMOT* (Palaeohydrogeological Data Analysis and Model Testing) och omfattar ytterligare utveckling av analysteknik och modelleringsverktyg för att utvärdera data. I projektet bedrivs dessutom forskning som syftar till att undersöka de specifika processer som beskriver kopplingen mellan klimat och grundvattenkemi i lågpermeabelt berg. Under 2002 har arbete pågått med att preparera och analysera prov från borrkärnor från ett djupt borrhål (KLX01) som ligger i Laxemar på fastlandet väster om Äspö. Bakgrunden till prov-/analysprogrammet är att kunna urskilja och karakterisera unga kalciter som bildats vid låga temperaturer. Proverna påvisar relativt djupa inflöden av både meteoritiska vatten och relikta smältvatten. Den 2–3 oktober organiserade koordinatorn för PADAMOT-projektet ett möte i Bryssel.

Förvarsteknik

I Äspölaboratoriet kan viktiga funktioner hos förvarets delar demonstreras och testas i full skala. Det är också viktigt att kunna visa att hög kvalitet kan uppnås vid utformning, byggande och drift av ett djupförvar. Ett flertal projekt pågår för att uppnå detta: ”Demonstration of Repository Technology”, ”Prototype Repository”, ”Backfill and Plug Test”, ”Canister Retrieval Test”, ”Long Term Tests of Buffer Material”, ”Pillar Stability Experiment”, ”Low-pH cementitious products”, ”KBS-3 method with horizontal emplacement” och ”Cleaning and sealing of investigation boreholes”.

Demonstration av deponering av kapslar under strålskärmade förhållanden i fullstor skala genomförs inom ramen för *”Demonstration of Repository Technology”* som omfattar testning av bentonit- och kapselhantering i fullstora deponeringshål. Testning och demonstration av deponeringsprocessen genomförs i till exempel det pågående projektet ”Prototype Repository”.

Projektet *”Prototype Repository”* fokuserar på test och demonstration av förvarskomponenters funktion i fullstor skala och delfinansieras av Europeiska Unionen. Projektet omfattar sex kapslar med elektriska värmare omgivna av högkompakterad bentonit som deponeras i fullstora deponeringshål. Installationen av fyra kapslar i den inre sektionen (Sektion I) avslutades under år 2001. Den ursprungliga planen var att fortsätta installationen i den yttre sektionen (Sektion II) under 2002. Men eftersom man upptäckt en felfunktion hos värmare av samma typ i ”Canister Retrieval Test” beslöt man att vänta med installationen av de två kapslarna i Sektion II tills man hittat en förklaring till felet. Under hösten 2002 fann man att de huvudsakliga orsakerna till problemen med värmarna var pyrolys av isoleringsmaterialet runt kablarna och utformningen av lockgenomföringarna. Baserat på dessa upptäckter utvecklades och konstruerades genomföringar med ny design. Det bedömdes inte vara nödvändigt att genomföra några speciella åtgärder för att förbättra förhållandena för de fyra redan installerade kapslarna. Enligt nuvarande planer kommer de två återstående kapslarna att installeras under år 2003. En generell slutsats efter 1,5 års drift är att mätsystemen fungerar bra. Förutom installationsarbeten och mätningar av driftförhållanden har även konceptuellmodellering och modelleringsutveckling bedrivits under året.

Testning av olika återfyllnadsmaterial, inplaceringsmetoder och pluggning av tunnlar genomförs i *”Backfill and Plug Test”*. Experimentet utgör en test av hydraulisk och mekanisk funktion hos tunnelåterfyllnadsmaterial samt dess inverkan på omgivande berg. Den 28 meter långa testregionen är lokaliserad till ZEDEX tunneln. Den inre delen av tunneln är fylld med en blandning av bentonit och krossat berg och den yttre delen är fylld med enbart krossat berg. Testregionen är indelad i sektioner med hjälp av permeabla mattor som används för konstgjord bevätning av återfyllnaden. Bevätning av återfyllnaden påbörjades i slutet av 1999. Vattentrycket i mattorna har höjts i steg och i januari 2002 togs det slutliga steget och trycket ökades till 500 kPa. Vattenmättnad, vattentryck och svälltryck i återfyllnaden samt vattentryck i det omgivande berget mäts kontinuerligt och registreras. I slutet av 2002 indikerade mätarna att hela återfyllnaden tycks vara fullständigt vattenmättad. Flödestesterna kan därför starta år 2003 som planerat.

”Canister Retrieval Test” är lokaliserad till huvudtestområdet på 420-metersnivån och syftar till att testa teknik för återtag av kapslar efter det att den omgivande bentonitbufferten har vattenmättats. En fullstor kapsel med elektriska värmare omgiven av bentonitblock och bentonitpellets har installerats i ett vertikalt borrat provdeponeringshål. Testet har varit i drift i lite mer än två år och vatten tillförs bentonitblocken kontinuerligt. Bevätningsprocessen, temperatur, spänning och svällning mäts och registreras fortlöpande. Värmarna har en defekt (se ”Prototype Repository” ovan) som orsakar ett mycket litet motstånd till jord. Trots detta har värmarna fungerat väl och man har beslutat att fortsätta testet. Av försiktighetsskäl har man dock minskat temperaturen till 80°C som mest på kapselns yta. Ett stort antal parametrar mäts under testet för att utgöra underlag för modellering. Instrumenten som mäter den relativa fuktigheten indikerar att bentoniten mellan bergväggen och kapseln är nära vattenmättad men bevätningen tycks vara något ojämn.

I *”Long Term Tests of Buffer Material”* genomförs långtidstester av buffertmaterial som syftar till att validera modeller och hypoteser relaterade till buffertens fysikaliska egenskaper samt processer som berör mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport vid förhållande liknande ett KBS-3 förvar. Testmetodiken innebär att paket som innehåller ett kopparrör med elektriskvärmare, kompakterad bentonit, instrumentering och kontrollutrustning placeras i 4 m djupa borrhåll med en diameter på 300 mm. När testet är slutfört tas paketen upp. Vattenmättnaden i leran bestäms, kemiska och mineralogiska analyser genomförs och fysikaliska tester utförs. Ett paket togs upp i slutet av 2001 och under 2002 har analyser genomförts på bentonitmaterialet samt på kopparkuponger och spårämnen som legat i bentoniten. En rapport med resultaten från testet håller på att tas fram. De återstående fyra paketen har fungerat bra och vattentryck, total tryck, temperatur och fuktinnehåll har mäts kontinuerligt.

Med syfte att demonstrera möjligheterna att förutsäga spänningsinducerade bergbrott runt deponeringshål i sprickigt berg har ett projekt initierats vid Äspölaboratoriet, *”Pillar Stability Experiment”*. Projektet är en komplettering till en tidigare studie som genomförts i URL i Kanada. I projektet kommer även buffertens påverkan på utbredningen av mikrosprickor runt deponeringshål att studeras. Under 2002 har numerisk modellering av experimentet genomförts och baserat på geologisk och hydrogeolisk information från fyra karaktäriseringsborrhål har en lämplig plats för experimentet valts.

Projektet *”KBS-3 method with horizontal emplacement* (KBS-3H)” är ett samarbetsprojekt som drivs av SKB och Posiva. Projektet delades upp i fyra delar: förstudie, design, byggnation och provning i Äspölaboratoriet samt utvärdering. Förstudien avslutades oktober 2002 och slutsatsen var att med avseende på teknik, ekonomi och långsiktig säkerhet är det värt att satsa på en fortsatt utveckling av KBS-3H metoden. En säkerhetsanalys av barriärernas funktion med avseende på skillnader mellan vertikal och horisontell deponering har även genomförts under 2002.

I projektet *”Cleaning and sealing of investigation boreholes”* ska bästa möjliga tillgängliga teknik för rensning och förslutning av undersökningsborrhål identifieras och demonstreras. Undersökningsborrhål borras under platsundersökningar och vid detaljerade karakteriseringar för att erhålla data om bergets egenskaper. Dessa borrhål måste rensas och förslutas senast vid den framtida förslutningen av det planerade djupförvaret. Vid rensning ska de instrument som suttit i borrhålens ofta aggressiva miljöer under långa tider avlägsnas. Därefter ska borrhålen förslutas vilket innebär att konduktiviteten i borrhålen inte får vara högre än i omgivande berg. En status rapport som sammanfattar teknikutvecklingen inom detta område under de senaste 10–15 har sammanställts.

Äspölaboratoriet

Målet med driften av Äspölaboratoriet är att garantera säkerheten för alla som arbetar eller besöker anläggningen samt att driva anläggningen på ett miljömässigt korrekt sätt. Driften av anläggningen under 2002 har fungerat programenligt och tillgängligheten på servicerelaterade system i anläggningen och underjordslaboratoriet har varit nästan 98 %. Ett nytt förrådsutrymme för underjordsutrustning togs i drift våren 2002. Byggnadsarbetet för att skapa nya kontorsutrymmen påbörjades i september 2002 och beräknats att vara klart våren 2003. Under 2002 har bergförstärkningsarbeten genomförts och vattendistributionssystemets kapacitet har förbättrats för att öka brandsäkerheten under jord.

Informationsgruppen ska i samarbete med andra avdelningar inom SKB skapa acceptans hos allmänheten för SKB:s verksamhet. Detta sker genom spridande av information om företaget, SKB:s pågående platsundersökningsprogram och de tre anläggningar som drivs i Oskarshamns kommun (Äspölaboratoriet, CLAB och kapsellaboratoriet). Under år 2002 besökte 10 000 personer Äspölaboratoriet och platsundersökningarna i Simpevarp. Det totala antalet besökare till alla anläggningar i Oskarshamnsområdet var 15 000 personer.

En viktig del av verksamheten vid Äspölaboratoriet är administration, drift och underhåll av instrument samt utveckling av undersökningsmetoder. Mätning och registrering av grundvattentryck, grundvattenflöden, och vattenkemi kräver effektiva system för datainsamling och datahantering. Detta hanteras via en direktanslutning till HMS (Hydro Monitoring System).

Internationellt samarbete

Under 2001 har åtta organisationer från sju länder deltagit i det internationella samarbetet vid Äspölaboratoriet förutom SKB. Flertalet av de deltagande organisationerna är intresserade av grundvattenströmning, radionuklidtransport och bergkaraktärisering. Flera av organisationerna deltar både i det experimentella arbetet vid Äspölaboratoriet och i modelleringsarbetet inom ”Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes”.

Enheten Djupförvarsteknik, inom SKB, koordinerar tre EU-projekt ”Prototype Repository”, ”Cluster Repository Project” (CROP) och nätverket NET.EXCEL. SKB deltar även i flera andra EU-projekt varav deltagandet i fem sker via enheten Djupförvarsteknik: FEBEX II, BENCHPAR, ECOCLAY II, SAFETI och PADAMOT.

Miljöforskning

I Äspölaboratoriet genomförs inte bara experiment som är fokuserade på radionuklidrelaterade processer utan även experiment som belyser frågeställningar som är av betydelse för icke-radioaktiva ämnen och deras miljöpåverkan. Äspö Miljöforskningsstiftelse grundades 1996 på initiativ av lokala och regionala intressenter, med målsättningen att göra Äspölaboratoriet tillgängligt även för miljöforskning.

Genom ett avtal mellan Miljöforskningsstiftelsen och Sveriges Geologiska Undersökningar (SGU) startade fältexperiment år 2001 i Äspölaboratoriet för att studera fördröjning och nedbrytning av petroleumprodukter under *in situ* förhållanden.

Kalmar universitet grundade under år 2002 Äspö forskarskola på initiativ av Äspö Miljöforskningsstyrelse. Målsättningen är att vid skolan ge förutsättningar för dagens och morgondagens miljöforskning.

Contents

1 General

1.1 Background

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

The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m, see Figure 1-1. The total length of the tunnel is 3600 m where the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The first part of the tunnel has been excavated by conventional drill and blast technique. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts.

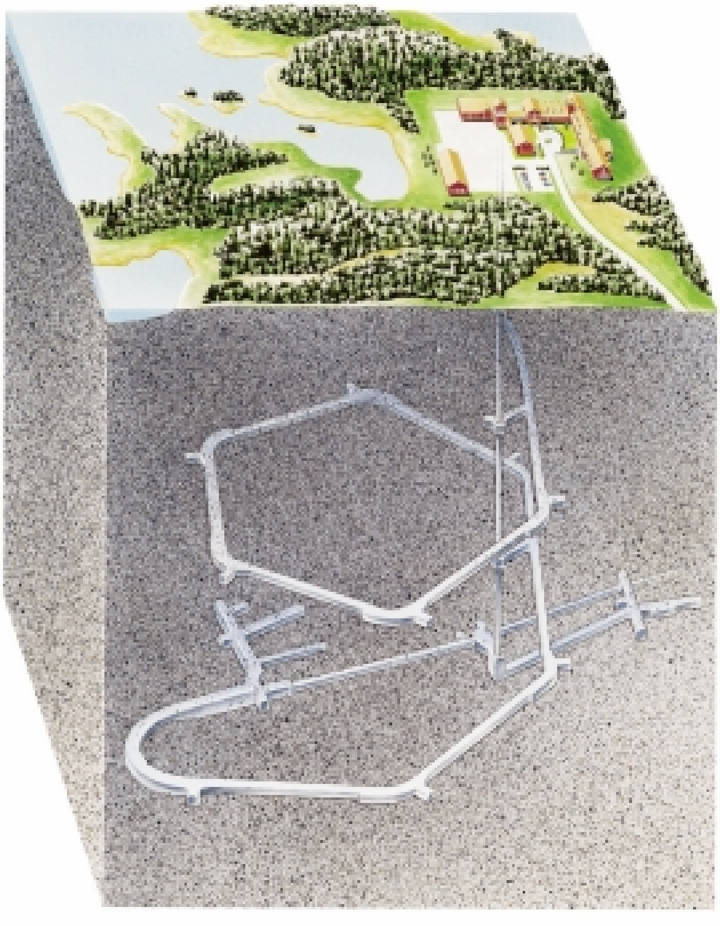


***Figure 1-1.** Overview of the Äspö HRL facilities.*

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

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

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

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

1.2 Goals

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

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

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

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

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

Stage goals 1 and 2 have been concluded and the tasks are transferred to the Site Investigation Department of SKB which, has began site investigations at two sites, Simpevarp in the municipality of Oskarshamn and Forsmark in the municipality of Östhammar.

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

- Develop, test, evaluate and demonstrate methods for repository design and construction, and deposition of spent nuclear fuel and other long-lived waste.
- Develop and test alternative technology with the potential to reduce costs and simplify the deep repository concept without sacrificing quality and safety.
- Increase the scientific understanding of the deep repository's safety margins and provide data for safety assessments of the long-term safety of the repository.
- Provide experience and train personnel for various tasks in the deep repository.
- Provide information to outsiders on technology and methods that are being developed for the deep repository.

1.3 Organisation

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

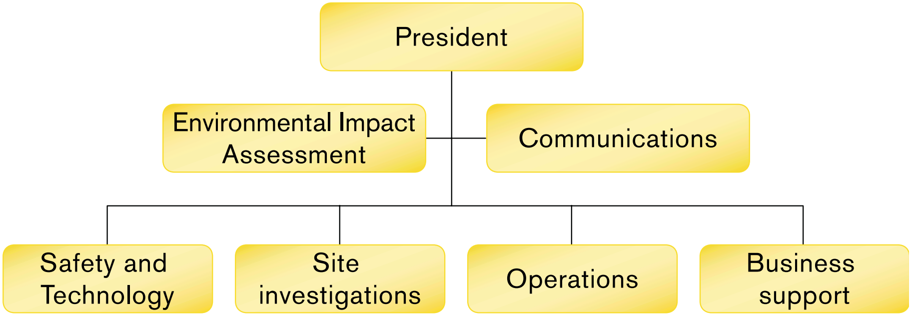


***Figure 1-2.** SKB's organisation.*

SKB's work is organised into four departments; Safety and Technology, Site investigations, Operations, and Business support. All research, technical development, and safety assessment work is organised in the Safety and Technology department, in order to facilitate co-ordination between the different activities. The Safety and Technology department is divided into five units:

- *Repository Design (TU)* is responsible for the design and layout of the deep repository. Presently site specific layouts are being developed for the two sites where site investigations are being performed. This department is also responsible for development of the technology needed to build, operate and seal the repository.
- *Repository Technology (TD)* is responsible for development and testing of deep repository technology and *in situ* research on repository barriers at natural conditions. The unit is also responsible for the operation of the Äspö facility and the co-ordination of the research performed in international co-operation.
- *Encapsulation Technology (TI)* is responsible for development and testing of the copper canister and the design of the Encapsulation Plant. This unit is also responsible for the operation of the Encapsulation Laboratory located in Oskarshamn.
- *Safety and Science (TS)* is responsible for research, safety assessments, and systems analysis.
- *Large Projects (TP)* is responsible for large construction projects.

1.3.1 Repository Technology and Äspö Hard Rock Laboratory

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

- *Technology and Science* is responsible for the co-ordination of projects undertaken at the Äspö HRL, for providing service (design, installations, measurements etc) to the experiments undertaken at Äspö HRL, to manage the geo-scientific models of the "Äspö Rock Volume", and to maintain knowledge about the methods that have been used and the results that have been obtained from work at Äspö HRL.
- *Facility Operation* is responsible for operation and maintenance of the Äspö HRL offices, workshops and underground facilities, and for operation and maintenance of monitoring systems and experimental equipment.
- *Administration*, *QA and Economy* is responsible for providing administrative service and quality systems.

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

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

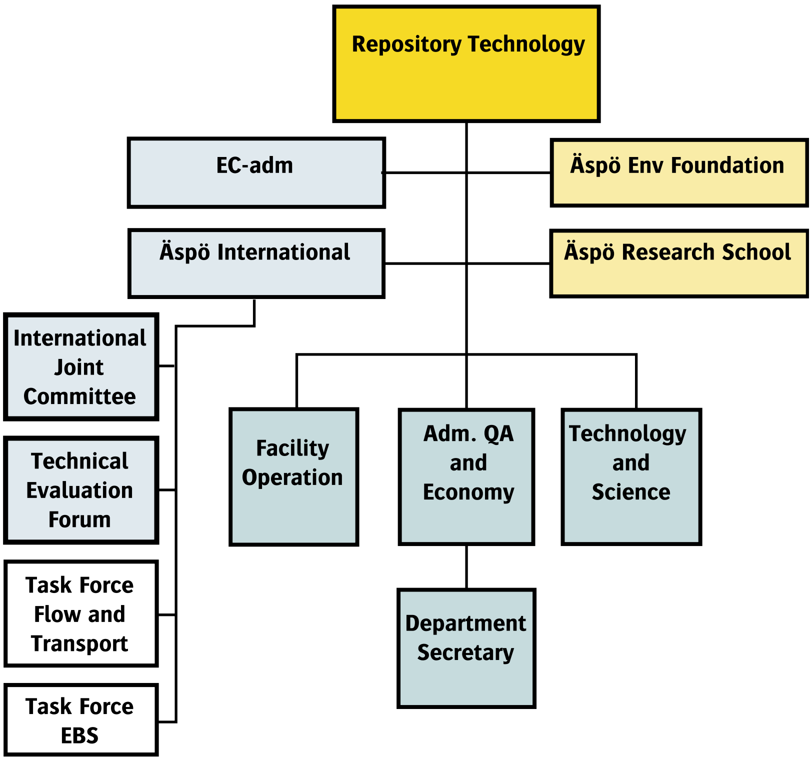


Figure 1-3. *Organisation of Repository Technology and Äspö HRL.*

1.3.2 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. Eight organisations from seven countries participated in the co-operation at Äspö HRL during 2002 in addition to SKB. The participating organisations were:

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

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

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

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

Some EC-projects are co-ordinated by the Director of Repository Technology and administrated by the Repository Technology staff. Examples are EC-projects concerning the Prototype Repository that has a direct coupling to the test set-up at Äspö, the CROP project that is coupled to experiments carried out in the Äspö HRL, and the PADAMOT project in which drill cores form the Äspö site are studied.

1.4 Allocation of experimental sites

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

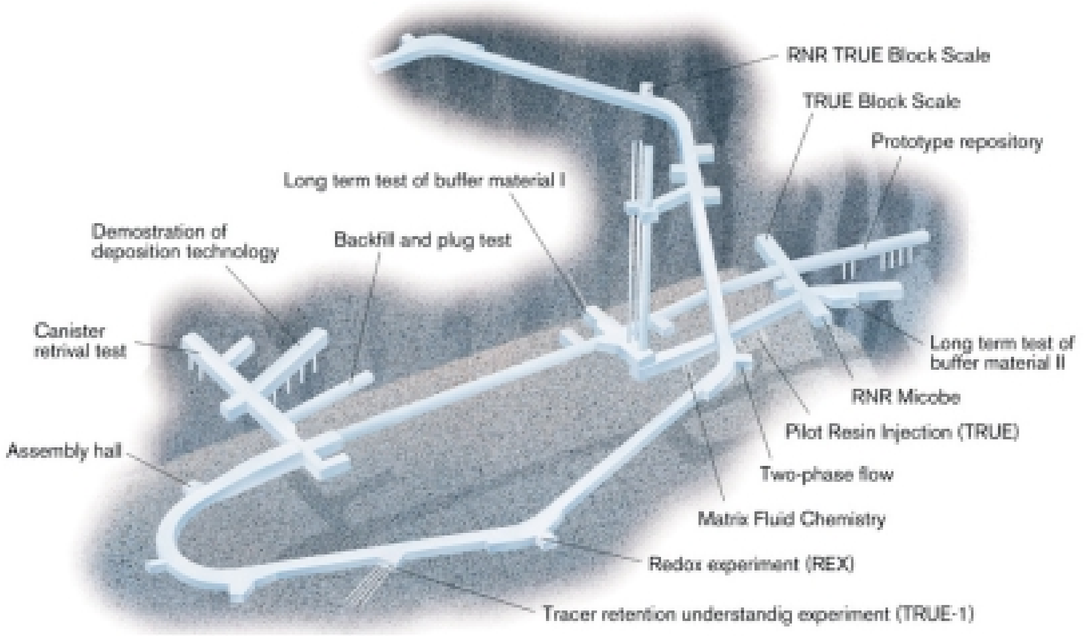


Figure 1-4. *Underground excavations at the 300–450 m levels and allocation of experimental sites.*

1.5 Reporting

Äspö HRL is an important part of SKB's RD&D-Programme. The plans for research and development of technique during the period 2002–2007 are presented in SKB's RD&D-Programme 2001 /SKB, 2001a/. The information given in the RD&D-Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report, which is revised annually. Detailed account of achievements to date for the Äspö HRL can be found in the Äspö HRL Annual Reports that are published in SKB's Technical Report series. In addition, Status Reports are prepared four times a year for internal distribution.

Joint international work at Äspö HRL as well as data and evaluations for specific experiments and tasks are reported in Äspö IPR. Information from Progress Reports is summarised in Technical Reports at times considered appropriate for each project. SKB also endorses publications of results in international scientific journals. Table 1-1 provides an overview of Äspö HRL related documents and the policy for review and approval.

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

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

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

1.6 Management system

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

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

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

SKB are constantly developing and enhancing the security, the environmental and quality-control efforts to keep up with the company's development and with changes in circumstances. One of the cornerstones of both the existing operations and in the planning of new facilities is the efficient utilisation of available resources.

The guiding principles of SKB's operations can be described as follows:

- A high level of security at all facilities.
- A low level of environmental impact.
- Efficiency.
- Meeting the demands imposed by legislation, statutes and regulations by a comfortable margin.
- Openness.

Project model

SKB has developed a project model for the implementation of projects. The aim of the model is to create an effective and uniform management of all projects. According to this model each project shall have a project owner and a project leader shall be appointed. A project decision describing the aim of the project and the resources as well as a project plan shall be prepared.

Environmental management

SKB manage Sweden's spent nuclear fuel and radioactive waste in order to safeguard the environment and people's health in both the short and long-term. This task is a key element of the national environmental objective of a safe radiation environment.

SKB make every effort to minimise their impact on the environment and the environmental work is goal-oriented and forms a natural part of all operations. Key assessment parameters for the selection of suppliers include security, environmental and quality aspects.

2 Natural barriers

2.1 General

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

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

The overall purposes are to:

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

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

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

Dilution is the third barrier function. It will take place in the rock volume surrounding the repository. The magnitude of dilution is very much depending on the site specific conditions. In the geosphere the dilution is caused by the dispersion in groundwater.

No experiment at Äspö HRL is focussing on dilution, although dilution is included in the biosphere safety assessment modelling.

The ongoing experiments and projects within the Natural Barriers at Äspö HRL are:

- Tracer Retention Understanding Experiments.
- Long Term Diffusion Experiment.
- Radionuclide Retention Experiments.
- Colloid Project.
- Microbe Project.
- Matrix Fluid Chemistry.
- PADAMOT.

In addition, conceptual and numerical models for groundwater flow and solute transport have been developed through the entire Äspö project. During 2002 the focus has been on further development of the numerical tools used for groundwater flow and transport calculations. A major part of this work is performed in the Äspö Task Force on Groundwater Flow and Transport of Solutes modelling work.

2.2 Tracer Retention Understanding Experiments

Background

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

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

The first *in situ* experiment (TRUE-1) performed on a detailed scale focused on an interpreted single fracture, was of limited time duration, and was primarily aimed at technology development, although comprehensive tests using radioactive sorbing tracers were included. The final report on the First TRUE Stage was presented by /Winberg et al, 2000/.

During 2002 work has been performed in the following sub-projects:

- TRUE Block Scale.
- TRUE Block Scale Continuation.
- TRUE-1 Continuation.

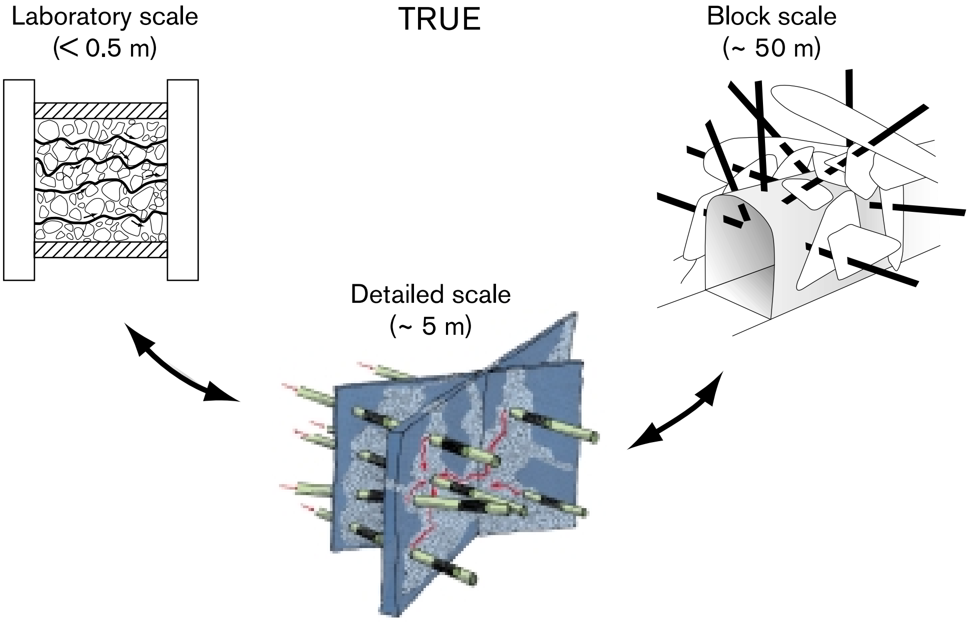


Figure 2-1. Schematic representation of transport scales addressed in the TRUE programme.

2.2.1 TRUE Block Scale

Background and objectives

Work on the TRUE Block Scale project started in mid 1996. This sub-project 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 100 m. The specific objectives of the TRUE Block Scale project are to /Winberg, 1997/:

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

Project stages

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

1. Scoping Stage.
2. Preliminary Characterisation Stage.
3. Detailed Characterisation Stage.
4. Tracer Test Stage.
5. Evaluation (and reporting) Stage.

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

A comprehensive summary of the findings of the latter three stages of the projects can be found in the Äspö HRL Annual Report for 2001 /SKB, 2002/. In the following sections an account of the concluding activities during 2002 is presented. This includes major conclusions from the two concluding volumes (III and IV) of the TRUE Block Scale Final Report dealing with transport modelling /Poteri et al, 2002/ and synthesis of results and achievements /Winberg et al, 2002/.

Results

Evaluation modelling

Evaluation modelling of the performed Phase C tracer tests (C1, C2, and C3) was finalised during 2002 and individual evaluation reports have been prepared based on the performed analysis using the five different modelling approaches; Stochastic Continuum (ENRESA-UPV/UPC), Discrete Feature Network (Nirex-Serco) and Pipe Channel Network (JNC/Golder), LaSAR (SKB-WRE) and the Posiva Streamtube approach (Posiva-VTT).

During the past year a large effort has been placed in trying to visualise modelling results in order to enable comparison between different approaches. This has been made in terms of (a) the parameter β which account for the hydrodynamic control for retention, (b) the parameter group κ which is a material properties group which accounts for the integrated effects of diffusion and sorption in the immobile zone(-s), cf Figure 2-2, and (c) individual retention parameters (e.g. porosity, pore diffusivity and sorption coefficient). Comparative measures of *in situ* retention were introduced and exploratory attempts were made to compare retention in the detailed scale (TRUE-1) with that seen in the block scale (TRUE Block Scale).

The hydrodynamic control of the retention (in terms of the parameter β /Poteri et al, 2002/) in different models can be estimated based on the information on the groundwater transit times and retention apertures. Figure 2-3 presents β's for different flow paths and different models. Flow path I (C1) shows a consistent grouping of most of the models showing values between 20 to 60 h/mm. It is noted, that flow path I gave breakthrough for the largest number of tracers and thereby the constraining power of the assembly breakthrough curves is highest for this flow path. The retention parameter β should increase with increasing path length which is also clearly visible in Figure 2-3 (estimated path lengths C1<C3<C2). The complexity of the flow path may have increased the spread between different models in the case of flow path II (C2). However, tracer tests C1 and C2 were performed using forced injection that may have had an impact on the parameter β. Normalising the parameter β for different flow rates and path lengths ($W=\beta/2\cdot q/L$), indicating an equivalent transport width of a uniform channel representing the physical flow path, shows values of W for the models that are 2 to 5 m for C1 and 0.2 to 1.5 m for C2 and C3. Generally, W is a factor of 3–5 higher for C1 than for C2 and C3.

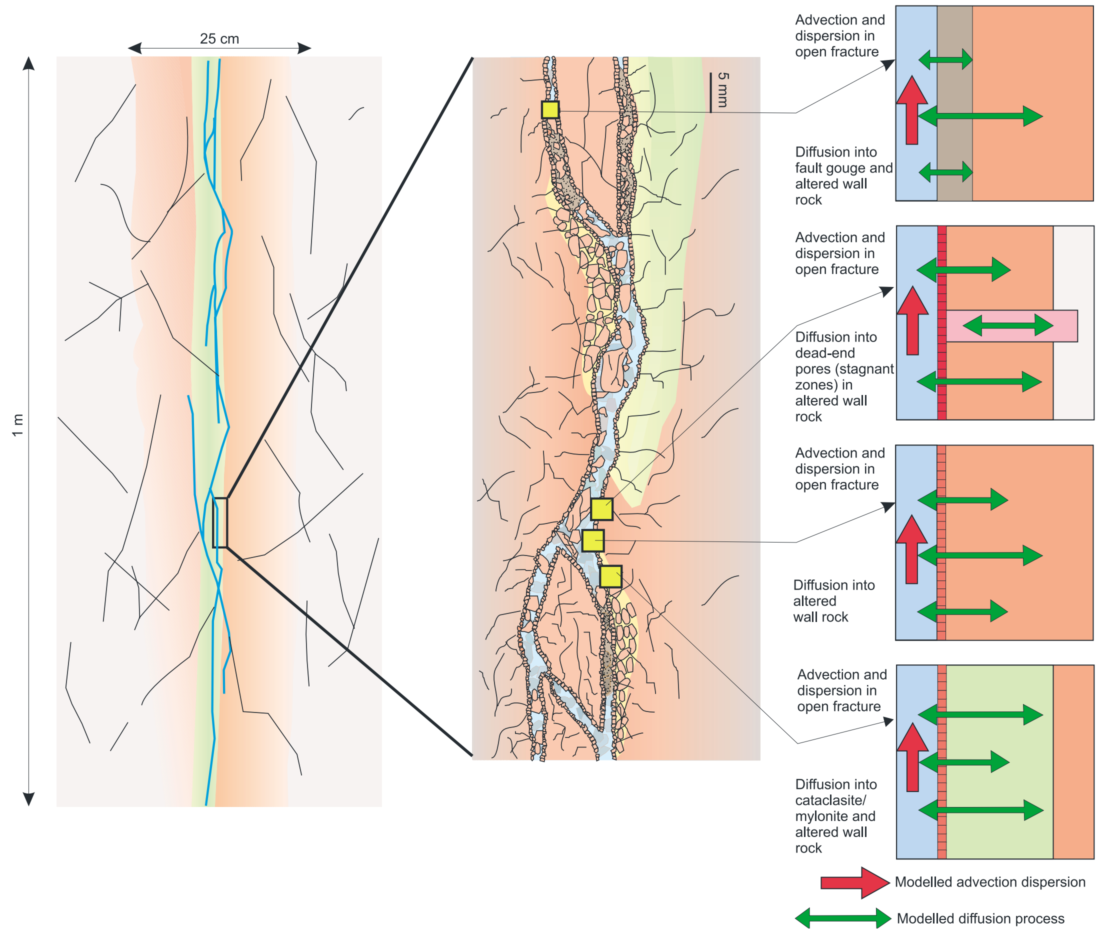


***Figure 2-2.** Simplification of the pore space structure as applied in the evaluation models.*

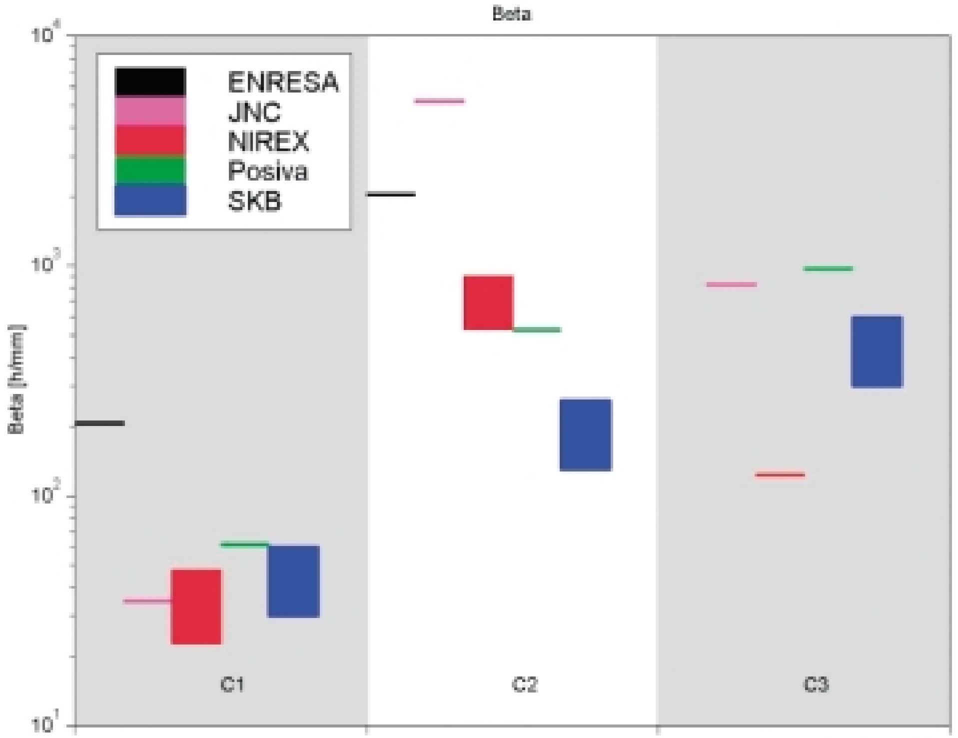


***Figure 2-3.** Evaluated parameter β which describes the average flow geometry of the flow paths of the various models and flow paths (tracer tests).*

A comparison of the evaluated material property group κ is shown in Figure 2-4. There is an obvious and clear separation between the models as to how they apply material properties in retention. The majority of the models apply material properties that are clearly higher than the MIDS (modelling input data set) values, the latter which indicate properties of the unaltered rock matrix /Winberg et al, 2000/. The stochastic continuum model (ENRESA-UPV/UPC) applies material properties that are comparable to the MIDS values. This is compensated by employing higher β values (cf Figure 2-3) in the evaluation.

/Poteri et al, 2002/ attempted an integration and illustration of the relative contributions to retention from the various processes/parameter groups included in the evaluation of the Phase C tracer tests. These are:

- Material parameter group κ, ($\kappa = \theta(D(1 + K_d \cdot \rho / \theta))^{1/2}$, where D is pore diffusivity, θ is porosity, ρ is density, and K_d is volumetric distribution coefficient).
- Hydraulic control parameter β.
- Surface sorption.
- Advection-dispersion.

In producing an illustration, see Figure 2-5, a simple weighting scheme was employed which indicates the relative importance put on a given process by a given model approach. The weights have been assigned subjectively by looking at the different processes included in the individual models. No direct and objective calculation method was employed to assess the relative importance. Nevertheless, the presented figure indicates the relative importance of the different retention and transport processes included in the final models used to evaluate the TRUE Block Scale Phase C experiments. The different approaches are ordered vertically in descending order in terms of the overall retention.

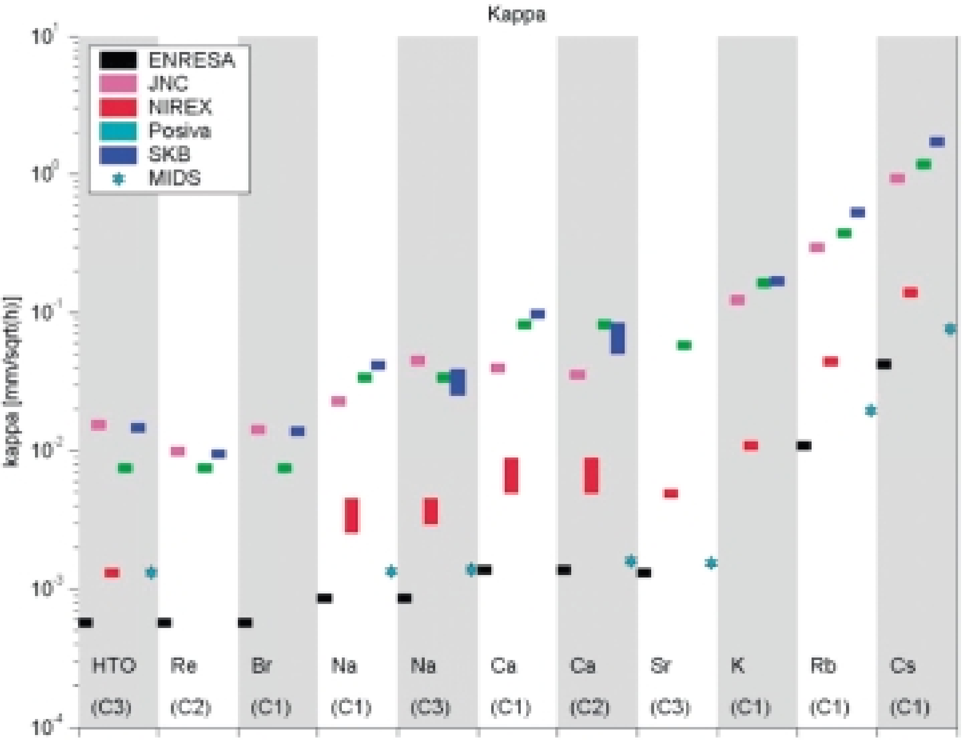


Figure 2-4. *Evaluated retention material parameter group κ for the respective evaluation models and tests (C1, C2 and C3).*

For the most part the noted differences between models in mapped contribution to retention are explained by the differences in the modelling of the advective field. Continuum models (ENRESA, Nirex) produce more variable advective transport than one-dimensional models (Posiva, SKB). The advective transport produced in the channel network model (JNC) is located somewhere in-between these two groupings. Hydrodynamic control of the retention through β is largest in the continuum model (ENRESA) where the flow may be divided between several fractures. The hydrodynamic control in the case of the one-dimensional models (Posiva and SKB) and the channel network model (JNC) is equitable. The diffusional coupling of the retention is adjusted by also changing the material properties group (κ).

Comparison of retention can be done in various ways and taking various aspects of retention into account. A basic measure, which only reflects the material properties that govern diffusion and sorption, is the parameter group (κ). An alternative measure, which also accounts for the hydrodynamic control, is the "Retention time" T_s /Poteri et al, 2002/. The latter measure is dependent on the flow path length/residence time and the injection flow rate. Yet an alternative measure is the "Diffusion time" t_d /Cvetkovic and Chen, 2002/ which is independent of the path length/residence time.

Looking at the retention in terms of the κ parameter group employed in the evaluation of the TRUE Block Scale Phase C tests, cf Figure 2-4, it is seen that retention for the non-sorbing conservative tracers used in the C1, C2 and C3 injections is similar. It is also noted that the κ used in the evaluation of Na (C1 and C3) and Ca (C1 and C2) are similar. A comparison with κ values used in the evaluation of the TRUE-1 (STT-1) and TRUE Block Scale C1 tests used by the Posiva-VTT teams shows similar values and hence similar retention in terms of the material properties group.

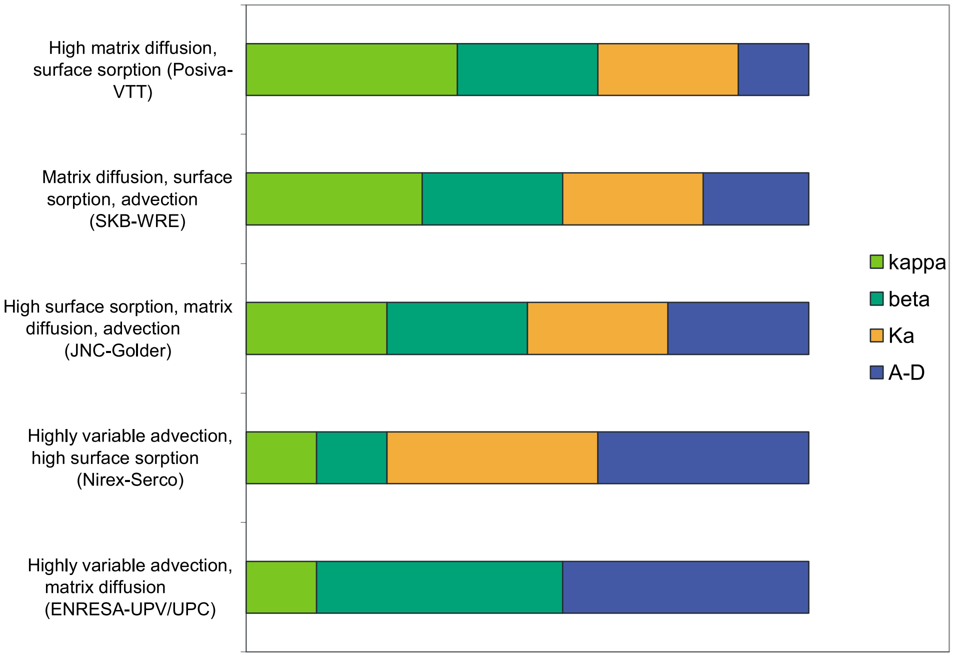


Figure 2-5. *Visualisation of subjective ranking of relative importance of retention and transport processes in models used to evaluate the TRUE Block Scale Phase C tracer tests.*

No rigorous comparison of retention in terms of T_s or t_d (both including effects of the hydrodynamic control) has been carried out between TRUE-1 and TRUE Block Scale project so far. However, tentative analysis indicates similar *in situ* retention when comparing the TRUE-1 and TRUE Block Scale flow paths e.g. when sorbing Cs is considered /Cvetkovic and Chen, 2002/.

The above indication of similar retention is indicative for crystalline rock similar to that found at the Äspö HRL. The result is potentially significant for performance assessment, as it implies spatial scaling effects in the "near zone" (corresponding to the distance from the repository to the nearest major (local) fracture zone) of a deep geological repository. It should, however, be pointed out that the temporal scaling, taking the step from experimental to performance assessment time scales, may have a strong impact on the result for a given micro-structural model and its parameterisation. The above indications will be subject to continued analysis in subsequent phases of the TRUE project.

Summary conclusions regarding block scale retention

The *in situ* experimentation and modelling of the TRUE Block Scale Phase C experiments have achieved the following major findings:

- It is demonstrated that the applied transport modelling approaches share the same basic theoretical basis. The difference between the approaches lies in how heterogeneity is introduced and parameterised.
- The observed *in situ* retention cannot be explained by surface sorption alone.
- All modelling groups assign matrix diffusion as an important, if not dominant retention mechanism. The existence of the diffusion process is also evidenced by characteristics of the measured breakthrough curves.
- Geological evidence indicates that other immobile pore spaces than the rock matrix are likely to exist along the studied TRUE Block Scale flow paths (e.g. fault gouge/fault breccia and stagnant zones).
- Porosity is significantly higher in the thin, peripheral layer of the altered fracture rim zone, and it decreases normal to the fracture to attain a background value of the intact unaltered rock several millimetres to a few centimetres away.
- Retention is governed by parameter groups (including descriptors for the flow field, immobile zone diffusion properties and sorption). It is therefore difficult to fully discriminate between the basic retention processes and come up with unambiguous *in situ* values on retention parameters without additional constraints. Such constraints are provided by site-specific and generic laboratory data on porosity and porosity distributions provide constraints in this context, as does site-specific laboratory data on sorption and diffusivity from the TRUE-1 site. Assignment of a low sorption coefficient may be compensated with a high diffusivity providing the same net result. Notwithstanding, the results show that with slightly different assumptions, reasonable *in situ* parameter values are retained/estimated.
- Heterogeneity in retention properties of the immobile zones (along and normal to the transport paths) may have an important influence on the interpretation of *in situ* results. Possibly most important is heterogeneity normal to fracture surface (effect on kinetics, effective properties) and may provide a partial explanation of differences between predictions based on laboratory retention data and *in situ* measurements).

- The observed *in situ* retention of the TRUE Block Scale flow paths is similar to that observed in the flow paths investigated as part of the detailed scale TRUE-1 experiments.
- No additional phenomena/processes are required to explain the results of the TRUE Block Scale. The same basic model used for single structures as applied to the TRUE-1 experiments is also applicable to a network of structures. This finding is attributed to the integrating nature of matrix diffusion process. It should be pointed out that it cannot be ruled out that the configuration of the tracer tests to some extent bias this conclusion (small source area, slight injection overpressure which generally results in 1D flow paths and single peak breakthrough curves).

Summary of major project accomplishments

Useful toolkits for site characterisation

The TRUE Block Scale project has confirmed the value of a number of powerful but uncomplicated characterisation techniques. Posiva flow logs identify the conducting intervals in boreholes with a high resolution. BIPS borehole imaging and BOREMAP core logging provide geologic descriptions of the conductors. Single-hole transient tests produce reliable information on hydraulic properties. Pressure monitoring during drilling and hydraulic testing indicates the connectivity along conductive features within the borehole array. Additional information from long-term pressure monitoring, hydrogeochemical sampling of groundwater, and background groundwater flow, provide a basis for conceptualising the flow system in the studied rock volume. It is noted that hydrochemical data provide support for a partly compartmentalised system.

Integrated network characterisation methods provide an adequate hydrostructural descriptive model in support of block scale experiments

Within the limitations imposed by the underground openings and possible collar positions for drilling, the borehole array provided an acceptable basis for establishing the hydrostructural model of the studied rock volume. The geological, geophysical, hydrogeological, and hydrochemical investigations have provided a satisfactory and mutually supporting basis for the *in situ* experimentation.

Improved description of porosity and porosity distribution

The laboratory data provided new insight into the heterogeneous nature of the studied flow paths. Improved understanding has been gained about the porosity characteristics of selected constituents of fault rock zones. Similarly, additional support has been presented regarding the decreasing trend in porosity normal to the fracture surfaces, observed already in conjunction with TRUE-1.

Improved microstructure conceptual models of conductive structures/fractures

Conceptual models for conductive fractures in fractured crystalline rock have been significantly improved through the work performed within the scope of the Fracture Characterisation and Classification project (FCC) /Mazurek et al, 1997; Bossart et al, 2001/ and TRUE programmes. Although the conceptual components are relatively well defined, it remains to fully parameterise some of its constituents (such as porosity/diffusivity of fine-grained fault gouge).

Simplified description of far-field from a performance assessment perspective

The results of the TRUE Block Scale experiments, thus far, do not require additional processes or features relevant to the safety case, which were not known from previous experience from TRUE-1. In addition, the results from tests with sorbing tracers, run over projected length scales 15–100 m, have shown similar retention to what was observed at the TRUE-1 site (5 m length scale). This finding, although of limited statistical significance, may indicate that complicated spatial scaling or parameters when taking limited steps in space is not important. It should in this context be noted that the effects of temporal scaling when taking the step from experimental to performance assessment time scales may not be that easy to assess.

Identification of retention data needs for repository site characterisation

Over the practical time frames of *in situ* experimentation, the retentive capacity provided by the near proximity rock adjacent to conductive fractures/flow paths will be involved in the retention of tracers. This combined with the defined parameter groups accounting for the individual retention processes, calls for improved laboratory quantification of diffusivity, porosity and sorption. It should, however, be emphasised, that a laboratory programme will never account for the exact mix of properties which the tracers will experience along a given flow path. Effectively we are only in a position to assess the situation at the source and at the sink. Exhaustive laboratory tests and statistical inference can in principle resolve this problem of uncertainty, but there is no guarantee to fully understand the particular flow path. In essence, we know the integrated response of a given flow path and our job is, to the best of our ability, to narrow down and constrain the *in situ* parameter estimates.

In the perspective of site characterisation for a geological repository, and subsequent performance assessment, the situation is different. Over the time span of a geological repository the retentive capacity of the close proximity rock (altered rim zones, fault breccia/fault gouge) will be consumed relatively quickly. This implies that the retentive capacity of the intervening rock blocks can be viewed as essentially infinite. However, this assumption is very much dependent on the extent of the connected porosity beyond the altered rim zone. At present, firm proof of infinite capacity is not available.

Inherent limitations in site characterisation with regards to collection of data relevant to performance assessment

The methodology employed in TRUE Block Scale does not provide a direct means to assess the flow-field controlled contribution to retention through parameters like β (or $2WL/q$), from site characterisation data alone. The parameter $2WL/q$ can however be estimated one the basis of geometrical inferences paired with flow data, the latter either from borehole flow data (ambient flow rate from tracer dilution tests) or from modelling. Alternatively the parameter β can be estimated using model simulation.

Evaluation of conservative assumptions

The improved conceptualisation and parameterisation of fracture rim zones and infillings can add additional, although limited, margin to safety. This applies especially to those radionuclides which are expected to be permanently fixated by clay minerals associated with the altered rim zones

2.2.2 TRUE Block Scale Continuation

Background and objectives

Midway through the TRUE Block Scale project it was identified that an interest existed to explore a continuation of the project. Since TRUE Block Scale was constrained by a relatively firm termination time (mid 2002) it was towards the end of the project identified that there existed some analyses which could not be accomplished within the set time schedule. It was also identified that any additional tracer experimentation should be based on issues/hypotheses posed by the numerical model evaluation of the TRUE Block Scale tracer test stage.

TRUE Block Scale Continuation (BS2) has in essence been in operation since December 2000, i.e. in parallel to the ongoing TRUE Block Scale (BS1). The main activity during this time has been complementary monitoring, sampling and analysis of the tails of the breakthroughs of the Phase C tracer injections (C1–C4). A second imminent component is modelling in support of planned *in situ* tracer tests to be performed as part of BS2B. Third, a water sampling and analysis campaign will be performed.

The TRUE Block Scale project /Poteri et al, 2002; Winberg et al, 2002/ identifies diffusion/sorption to available immobile pore spaces as the main retention mechanism. It is not known unambiguously which part of the immobile pore space(-s) that contributes to the bulk of the observed *in situ* retention. It is further noted that the evaluated *in situ* retention parameters are enhanced compared to the available laboratory-derived retention parameters for the (unaltered intact) rock matrix used in model predictions of the performed tracer experiments.

The remaining critical issues are related to the observed enhanced retention relative to available laboratory data. Is this an effect of high porosity immobile zones (fault gouge/rim zone) as stated by the project group, or is it in fact an effect of under-estimation of the area exposed to flow (transport) along the studied flow paths? Further, can the assessment of the available immobile zones assumed present along the flow paths and their relative contribution to retention be improved?

Experimental degrees of freedom are limited by the present installations in relation to the studied network of structures. However, attention in the modelling is placed on assessing the possibility to make use of (low-permeable) background fractures for injection as well as the possibility to perform tracer tests over longer distances. Process identification measures include variable flow rates and possible use of ideal non-sorbing tracers.

It is noted that the TRUE Block Scale Continuation project may not "resolve" conclusively any of the issues put forward. However, the project will at any rate improve understanding of key issues identified within the project related to block scale transport issues related to geometry, hydrogeology and solute retention, including effects of micro-structure.

It should in this context be mentioned that description and quantification of *in situ* porosity of fault gouge, using epoxy resin impregnation and complementary laboratory sorption tests on rim zone and fault gouge material are components included in the TRUE-1 Continuation project.

Results

The prolonged sampling and analysis of the Phase C breakthrough has been in progress from December 2000 till late fall 2002. The analysis part has included application of selective enrichment techniques to lower the detection limit for e.g. Cs. The continued sampling and analysis has enabled improved description of the tail of the ^{134}Cs for the C1 injection /Byegård, 2002/, cf Figure 2-6. Similarly, an improved description of the tail of the ^{22}Na breakthrough for the C3 injection has been obtained. However, the most rewarding feat was firm establishment of breakthrough of ^{137}Cs for the C2 injection, cf Figure 2-7. This breakthrough occurs after some 7000–8000 hours, i.e. after some 9–11 months after injection.

A comprehensive groundwater sampling campaign was conducted in the TRUE Block Scale borehole array in December 2002. A total of 23 test sections were sampled according to Class 5 and were also sampled for radon content. Selected sections were also sampled for analyses of U, Th, Cs, La, Yb using ICP (SGAB) and ^{226}Ra, ^{228}Ra, ^{222}Rn and U- and Th-isotopes (Studsvik). A remaining 19 sections were sampled according to Class 2 (including ^{18}O, ^{2}H and ^{3}H). Analysis results are expected during the first half of 2003. The results are expected to provide additional information which can help condition the hydrostructural model and the groundwater flow conditions in the TRUE Block Scale rock volume.

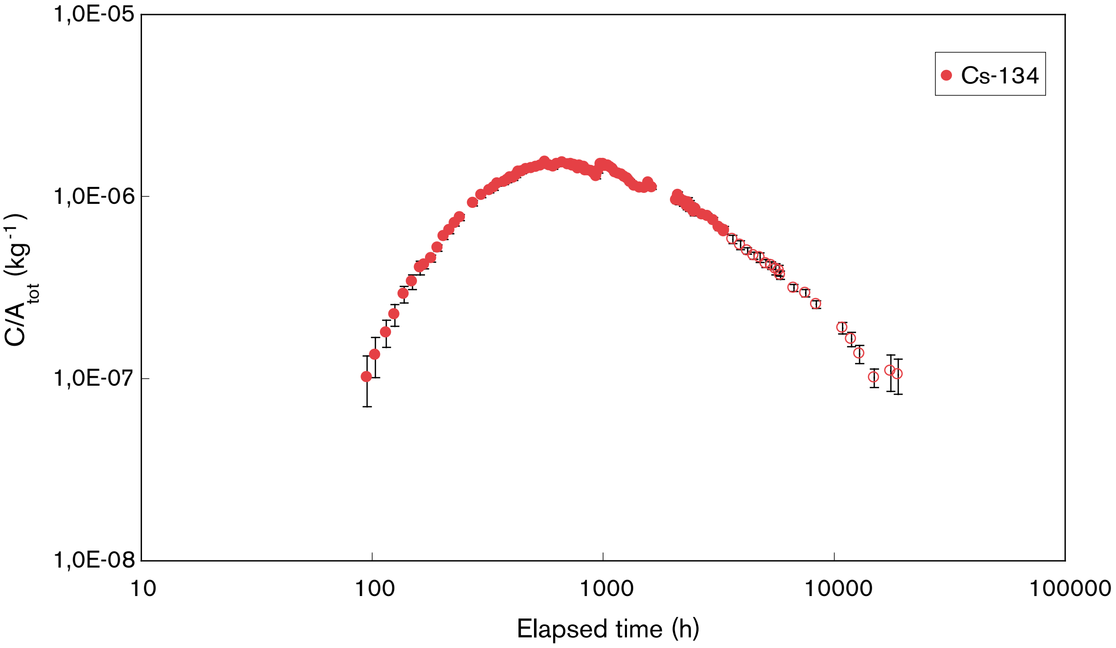


Figure 2-6. *Results of the continued sampling and γ-spectrometry measurements of ^{134}Cs$^+$, injection C1. The results are given as the measured tracer concentration (C, Bq/kg) in the withdrawal water divided by the total amount of tracer (A_{tot}, Bq) used in the injection. The filled circles refer to the result given in the previous report /Andersson et al, 2002/ and the open circles refer to results measured during the continuation part of the TRUE Block Scale Phase C experiment.*

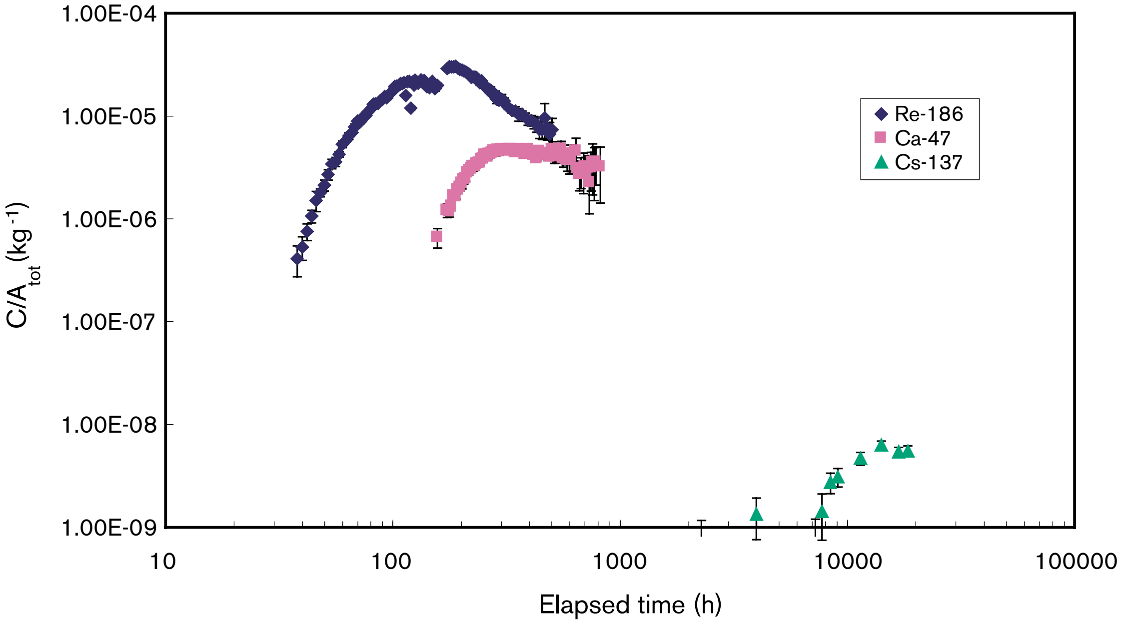


Figure 2-7. *Breakthrough of* $^{137}Cs^{+}$ *given in comparison with the other tracers (*$^{186}ReO_4^{-}$ *and* $^{47}Ca^{2+}$*) used for injection C2.*

2.2.3 TRUE-1 Continuation

Background

The First TRUE Stage, TRUE-1, was completed mid 2000 /Winberg et al, 2000/. The project team evaluations of the tracer tests with radioactive sorbing tracers /Cvetkovic et al, 2000/ attributed the noted retention to matrix diffusion and sorption onto the inner surfaces of the rock matrix. It was also interpreted that the magnitude of the *in situ* retention parameters was elevated compared to the available laboratory data (primarily based on intact Äspö diorite). These evaluation results were also based on the interpretation that the investigated Feature A could be regarded as sufficiently well isolated single near-planar structure, or a set of co-planar hydraulically connected fractures related to reactivated mylonite(-s) between the utilised source and sink sections. It should also be mentioned that alternate predictions and evaluations were performed using a wide variety of model approaches within the framework of the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, see Section 2.8.1.

An alternative conceptual model, where the investigated rock is made up of a well-connected fracture network in which a possible Feature A may be present is proposed by /Bossart et al, 2001/. Likewise, the interpretation of a planar singular feature is questioned by Moreno and Neretnieks /SKB, 2001b/. They interpret the noted enhancement in retention as being an effect of a more 3D flow pattern invoking parts of the fracture network proposed by /Bossart et al, 2001/. /Mazurek et al, 2003/ and /Jakob et al, 2003/ attribute the bulk of the noted retention to a more complex (sandwiched) structure of the flow path (exposing more surface area), accessing fine-grained fault gouge, attributed a high porosity (10–30%). In conclusion, the available data (lack of data) invite to conceptual uncertainty.

Objectives

The specific objectives of the complementary work at the TRUE-1 site are:

- To obtain insight into the internal structure of the investigated Feature A, in order to allow evaluation of the pore space providing the noted retention in the performed experiments.
- To provide insight into the three-dimensionality of the rock block studied as part of the First TRUE Stage, such that the role and effects of the fracture network connected to Feature A on the performed tracer tests can be assessed. A preliminary exercise includes characterisation of fault rock zones including e.g. epoxy resin techniques.
- To test a methodology to assess fracture aperture from radon concentration in groundwater combined with radon flux from geological materials.

Experimental concept

The route planned to be taken to resolve the conceptual uncertainty includes a series of steps:

- Complementary cross-hole interference tests, tracer dilution tests, and tracer tests, which involves alternate source and sink sections proceeded by re-instrumentation of selected piezometers. These activities are complemented with the test of methodology to assess fracture aperture by radon measurements described above.
- Complementary laboratory tests in order to verify the sorption properties of altered wall rock, mylonite, and fine-grained fault gouge. TRUE Block Scale and generic geological material from fault rock zones at Äspö HRL.
- Characterisation of fault rock zones including attempts to measure the *in situ* porosity of fine-grained fault gouge material using some type of resin. The characterisation work include geology/structural geology, mineralogy/geochemistry, detailed description of resin-filled pore spaces and sorption properties (K_d) of fine grained fault gouge,
- Application of the developed resin injection technology /Birgersson et al, 2000/ to the TRUE-1 site. The application of the resin technology to the TRUE-1 site is conditioned on the performance and termination of the Long Term Diffusion Experiment, see Section 2.3.

Results

Complementary *in situ* tests

The *in situ* investigations included three pressure interference tests combined with tracer dilution tests and two multiple-hole tracer tests using conservative tracers. The main objective of the tests was to obtain more information about the fracture network which the target structure Feature A is part of, and Feature A's relation to this network. The results of the tests confirm the hydro-structural model of the TRUE-1 array consisting of at least three well separated hydraulic units, Feature A, Feature B+D and Feature NW-2. This conclusion is also supported by a tracer test where no tracer transport between Features A and B could be detected. Hence, the flow regime may not be considered as three-dimensional in the scale of the tracer tests (up to 10 m). The tracer tests also confirm that the flow path used in earlier tracer tests (e.g. STT-1 and STT-2 /Winberg et al, 2000/) consists of two separate transport paths with similar transport properties.

In situ radon measurements for fracture aperture determinations

Experimental activities have been performed in order to investigate the possibility of assessing fracture apertures from radon concentrations in groundwater /Byegård et al, 2002/. A new method for sampling groundwater and maintaining overpressure during the γ-spectrometry measurement has shown that reproducible results can be obtained. By sampling at the TRUE-1 site at the Äspö HRL and performing subsequent radon measurements, indications have been obtained that radon concentrations are very similar for waters sampled from the same identified geological structures, see Figure 2-8.

Laboratory experiments have been done in order to see if a simple diffusion cell approach combined with liquid scintillation measurements with pulse shape analyses (PSA) can be used to measure radon fluxes from intact rock surfaces. The results are very promising and indicate that determination of radon fluxes from most rock materials should be possible to perform.

Radon fluxes have also been estimated from some different fault gouge materials; all sampled at the Äspö HRL. The results provide no evidence that the flux from the unconsolidated gouge material in the fracture should be the dominant source for the radon in the groundwater.

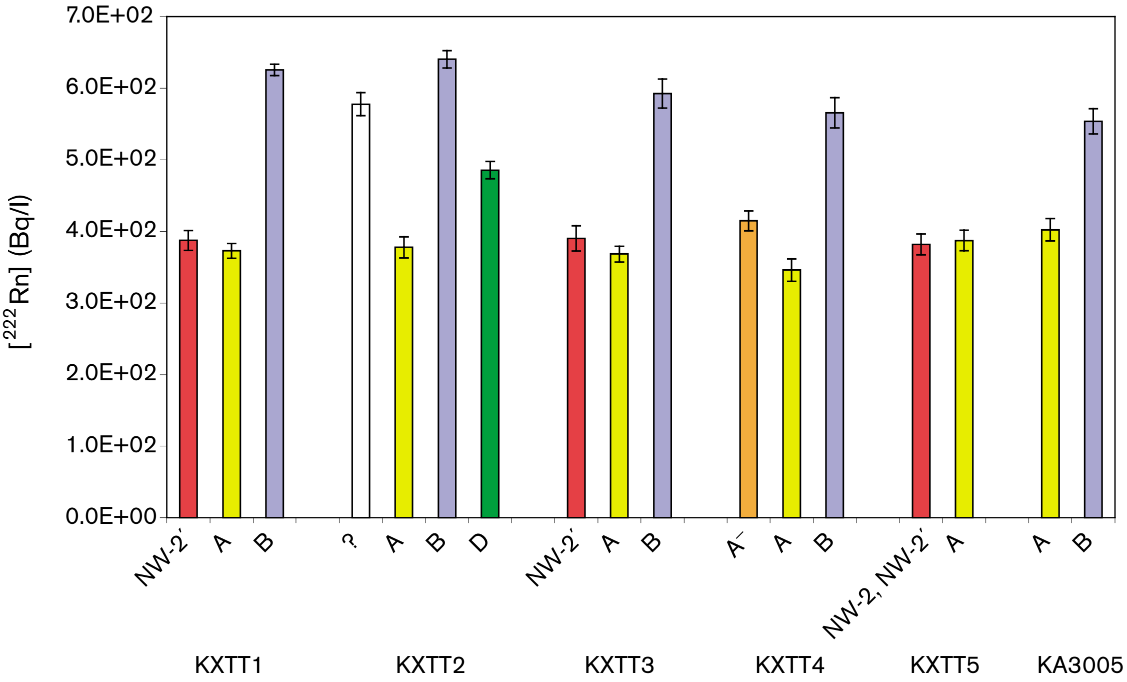


Figure 2-8. *Radon concentration in sampled groundwater in the TRUE-1 site. Results are given for the two campaigns, November 2001 (top) and December 2001 (bottom). The results refer to the different boreholes (KXTT1–KXTT5 and KA3005) and the isolated sections in these boreholes which correspond to different features (see /Winberg et al, 2000/ for further details).*

Characterisation of fault rock zones

The experimental concept builds on drilling of a fan of short exploration boreholes from the tunnel into the fault rock zone. Following necessary characterisation work, the boreholes will be packed off with mechanical packers producing a test section which will include a PVC dummy. Resin will be injected and will be followed by overcoring using a larger diameter 300–400 mm. The cores will be analysed with respect e.g. to pore space and porosity. The characterisation work will serve to fill in the gaps of the databases related to the ongoing TRUE experiments at the Äspö HRL. The generic nature in the search, and also the variable dignity foreseen in the investigated fault rock zones, implies that general knowledge will be collected which can be used to improve conceptual models of fault rocks, not only for Äspö HRL and its experiments specifically, but also in a more general sense. The latter component means that the collected information can be used in support of the site characterisation programme recently started up in Sweden.

Work performed during 2002 included identification of four candidate fault rock zones at various depths in the Äspö HRL. Furthermore, a drill core of fault gouge material was extracted from one of the zones (NE-2 at 1/600 m) which will be subject to laboratory experiments to test out optimal resin recipes and dye additives. Figure 2-9 is a photograph showing the extracted 200 mm core.

Figure 2-9. *Photograph of core drilled in Fracture Zone NE-2 parallel to the chlorite rich layers.*

2.3 Long Term Diffusion Experiment

2.3.1 Background and objectives

The Long-Term Diffusion Experiment (LTDE) is intended as a compliment to the *in situ* dynamic experiments and laboratory experiments performed within the TRUE programme, cf Section 2.2.

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

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

2.3.2 Experimental concept

The original test plan /Byegård et al, 1999/ presented an experimental concept centred on establishment of an experimental (large diameter) borehole exposing a natural fracture surface. This fracture surface was meant to be packed off with a cylindrical cap, similar to the one used in the REX experiment. The intention was to establish an experimental chamber in which a tracer solution could be circulated over a period of four years, after which the rock volume involved would be excavated and analysed for tracer content. Performed scoping calculations using available diffusivity data indicate 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 were considered. The principal challenge of the experiment was to establish axial diffusion from a natural fracture, through the rim zone of fracture mineralisation and alteration, into the unaltered rock matrix, without any advective flow component (towards the tunnel). This was planned to be resolved by using a multi-packer system which effectively would shield off the gradient. In addition, an intricate pressure regulation system will be devised which will effectively allow the pressure in the experiment chamber to adapt to the ambient conditions without causing pressure differences, and hence no induced advective transport. The reference pressure will be 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 large diameter experimental borehole.

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

2.3.3 Results and achievements

Drilling, characterisation, and structural modelling

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 in KA3065A02 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 which is considered as the target volume for the diffusion experiment.

The drilling of the telescoped large diameter experimental borehole was performed with a high degree of interactivity between; careful iterative drilling in short uptakes (particularly in the inner part of the borehole), BIPS imaging, core examination and on-site structural modelling/updating of structural model, cf Figure 2-10. The original plan was that the target fracture should be intercepted and passed in such a way that an approximately 50 mm long core "stub" would remain 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. 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.

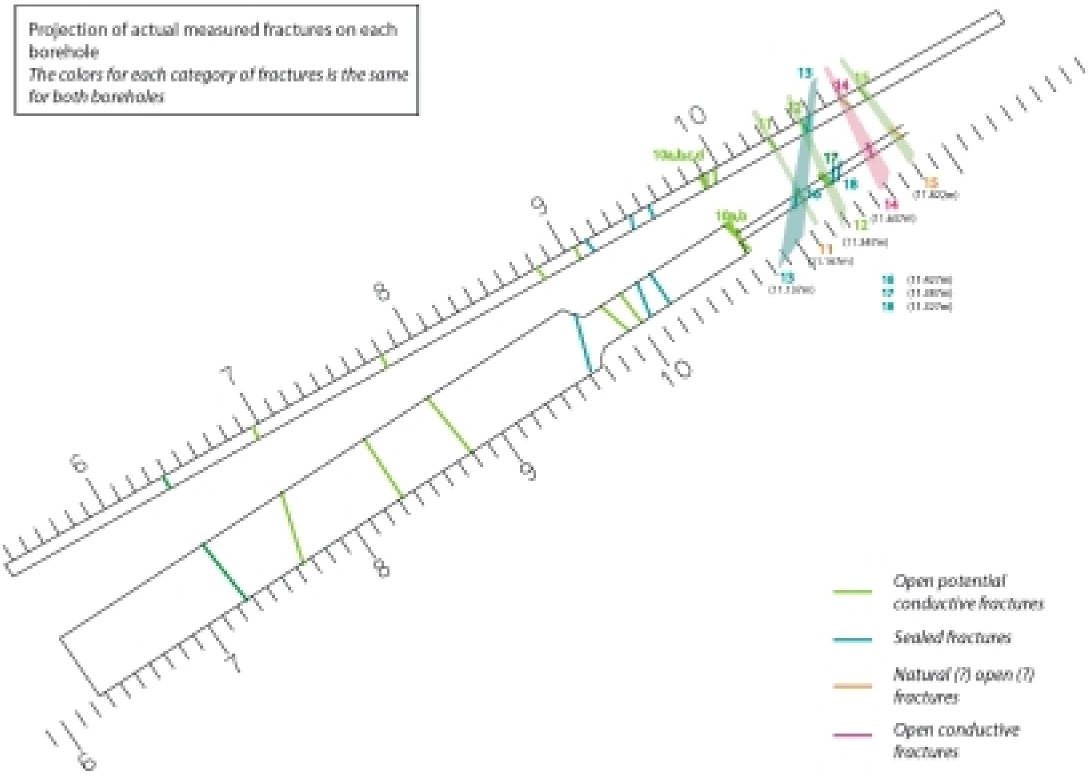


Figure 2-10. Basic structural model of the LTDE rock volume.

As pointed out above, the core stub length in KA3065A03 turned out to be 150 mm, i.e. three times longer than the originally planned 50 mm. The projected diffusion length in the core is three times longer than originally planned. The diffusion front for the least sorbing 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; (a) stress concentrations associated with the advancing drill bit, and (b) unloading of stress acting of the remaining core stub. 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 above, a series of *in situ* and laboratory measurements have been conducted during 2001 which have been compared with existing *in situ* Äspö data/results and information found in the literature. 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. Notwithstanding, the effect is there and effectively led to discarding the core stub for *in situ* estimation of diffusivity. Alternative concepts were assessed and eventually one where the intact rock is accessed using a small diameter borehole through the centre of the core stub was selected, see Figure 2-11.

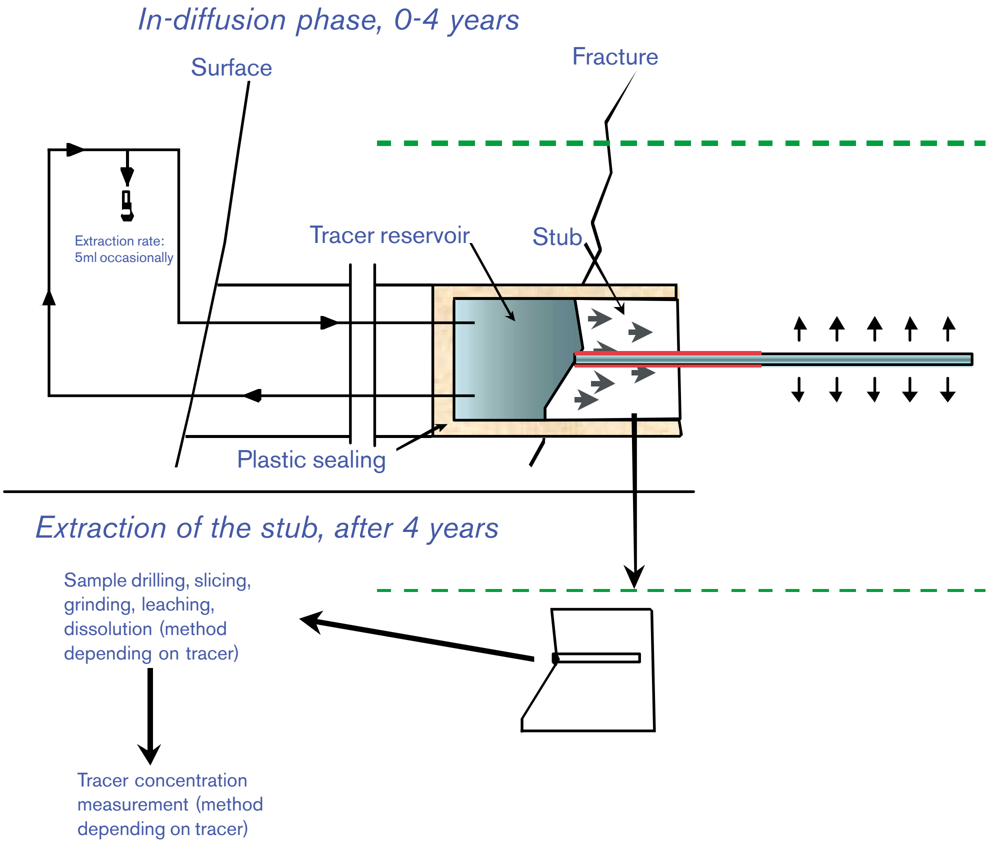


***Figure 2-11.** Schematic of LTDE experimental concept including injection borehole in contact with a fracture surface, an injection section in intact rock and schematically outlined overcoring (hatched green) and penetration profile studies.*

Following a comprehensive update of the structural model of the investigated site, drilling was carried out with careful drilling methodology in two separate uptakes. The length of the core is about a metre. The core was examined and the borehole was logged using a forward-looking TV-camera. The resulting model is presented in Figure 2-10. The basic result was that the borehole extension, with the exception of its end parts, was essentially dry. A series of flow tests were conducted in order to (a) establish whether the identified discontinuities were conductive, and (b) whether the noted conductive fracture in the bottom of the borehole could be used to bleed of any pressure increase following installation of the packer system. The results of the analysis enabled identification of 30 cm long test section in a part of the borehole which includes intact, unaltered rock plus a sealed fracture. The actual test will hence enable study of diffusion also in a well defined sealed hairline fracture.

New equipment parts and installation of equipment in borehole

The new component in the equipment is made up of a mechanical double packer and a docking device connecting the new packers system with the old packer system. The borehole equipment (see Figure 2-12) was installed late June 2002. Subsequently various, pressure build-up tests, short-term interference tests and groundwater sampling for chemical and microbe analyses have been collected.

Infrastructure

The experimental equipment is installed in two containers. All equipments for water circulation to the test section are installed in glove boxes that are flushed with nitrogen gas in order to avoid contact with air (oxygen). All equipments in the borehole and outside are constructed so that water from the test section only is in contact with PEEK material. The circulating system consists of:

- A pump for water circulation.
- A flow meter.
- A pressure regulator.
- Filter holders.
- A electrochemical cell for on-line pH and Eh measurement.
- Injection- and sampling-valves.
- Shielded cells for on-line activity measurement.
- Pressure and temperature measurement.

The experimental equipment and other sensors are connected to a process logic control (PLC) unit in order to accomplish the possibility for remote control.

Figure 2-12. Cap fitting to the surface of the stub and polyurethane cylinder assembled with mechanical packer (centre of upper photograph) and hydraulic packer far right. At this time double packer in the slim hole is already in place. The docking device which connects to the double packer is seen in detail in the lower photograph.

Identified problem areas

During 2002 a number of problem areas were identified which are described below:

- Excavation work at two sites in Äspö HRL during 2003 is expected to produce hydrological interference at the LTDE site. In order to avoid pressure variations and transients and several practical interferences, LTDE will start when more stable conditions are achieved in Äspö HRL.
- Microbes have been detected in water from the experimental test section in LTDE. Precautions to avoid uncontrolled build-up of bacteria and the possible formation of bio-films will be taken.
- Instrumentation of the experimental borehole KA3065A03 is complicated. A test programme has been initiated in order to control the behaviour of the borehole instrumentation under extreme circumstances.
- The control unit for pressure regulation did not work properly during installation and has now been repaired. In order to avoid unknown similar future problems, a test programme for each electronic device and subsequently a total system test under extreme conditions is planned.

2.4 Radionuclide Retention Experiments

2.4.1 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 by the conditions of the water conducting fractures and the groundwater flow.

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

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

2.4.2 Objectives

The objectives of the radionuclide retention experiments are:

- To validate the radionuclide retention data which have been measured in laboratories by data from *in situ* experiments.

- To demonstrate that the laboratory data are reliable and correct also at the conditions prevailing in the rock.
- To decrease the uncertainty in the retention properties of relevant radionuclides.

2.4.3 Experimental concept

CHEMLAB 1 and 2 are borehole laboratories built into probes, in which *in situ* experiments can be carried out under ambient conditions with respect to pressure and temperature, and with the use of natural groundwater from the surrounding rock. Initially one "all purpose" unit, CHEMLAB 1, was constructed in order to meet any possible experimental requirement. At a later stage, a simplified version the CHEMLAB 2 unit was designed to meet the requirements by experiments where highly sorbing nuclides are involved. Figure 2-13 illustrates the main components of the CHEMLAB 1 and CHEMLAB 2 units.

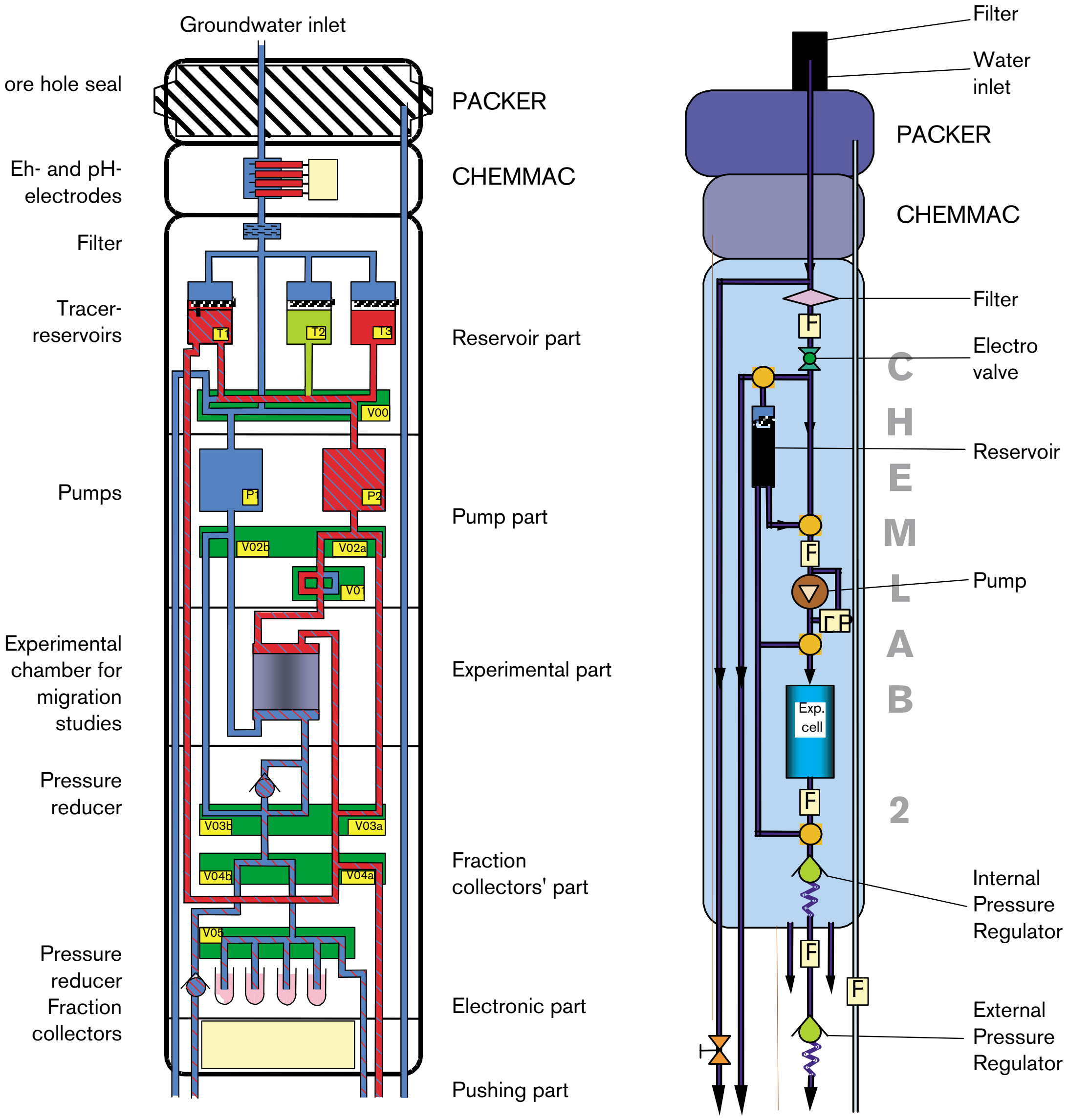


Figure 2-13. Schematic illustration of CHEMLAB 1 and 2.

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

- Diffusion of anions and cations in bentonite.
- Influence of primary and secondary formed water radiolysis products on the migration of the redox-sensitive element technetium.
- Migration of actinides (americium, neptunium and plutonium) in a rock fracture.

2.4.4 Results

Diffusion in bentonite

Experiments on diffusion of cations (Co^{2+}, Sr^{2+}, Cs^{+}) and anions (I^{-} and TcO_4^{-}) in compacted bentonite clay has been carried out with the CHEMLAB 1 unit. During 2001, the results were reported in a final report /Jansson and Eriksen, 2001/. The main finding is that the measured concentration profiles for Co^{2+}, Sr^{2+}, Cs^{+}, I^{-} and TcO_4^{-} are in good agreement with modelling predictions based on apparent diffusivities and sorption coefficients obtained in laboratory experiments.

Radiolysis experiments

Since oxidising species are produced at water radiolysis, there is a possibility that redox sensitive radionuclides are oxidised. For such nuclides, e.g. technetium, neptunium, plutonium, and uranium, a change in valence state increase their mobility. The radiolysis experiments are diffusion experiments in compacted bentonite clay, where the water is irradiated and the influence of formed radiolysis products on the radionuclide mobility will be studied.

In the end of 2002, two kinds of radiolysis experiments were started. In the indirect radiation experiments, the water is irradiated before it comes in contact with the cell containing the bentonite and the radionuclide. The radicals produced from water radiolysis will not reach the experiment cell, only molecular products, H_2O_2, O_2 and H_2 will influence the redox chemistry of the experimental cell. In the direct radiation experiment, the irradiation source is placed in the experiment cell, close to the reduced technetium, and thereby the radicals produced will play a role. The radiolysis experiments are planned to be terminated in the beginning of April 2003.

Migration of actinides

In these experiments an actinide containing cocktail is added to the groundwater before pumping it through a longitudinal natural fracture of a core placed in CHEMLAB 2. The first experiment carried out in CHEMLAB 2 was the migration of actinides, americium, neptunium and plutonium in a rock fracture. Pre-studies have been performed at Institut für Nukleare Entsorgung at Forschungszentrum Karlsruhe (INE) using cores taken from Äspö HRL. During fall 2001 until February 2002 INE carried out the second of several actinide migration experiments at Äspö in co-operation with SKB staff and Nuclear Chemistry at the Royal Institute of Technology. The results have been evaluated and published as a FZK/INE report /Römer et al, 2002/. These results together with those of the preliminary laboratory investigations with the same type of cores were presented in the MRS 2002 Conference, workshop on "Scientific basis for Nuclear Waste Management" and are accepted for publication in the MRS Symposium proceedings /Kienzler et al, 2002/. The breakthrough of neptunium and HTO determined in CHEMLAB 2 and in the laboratory experiments is presented in Figure 2-14.

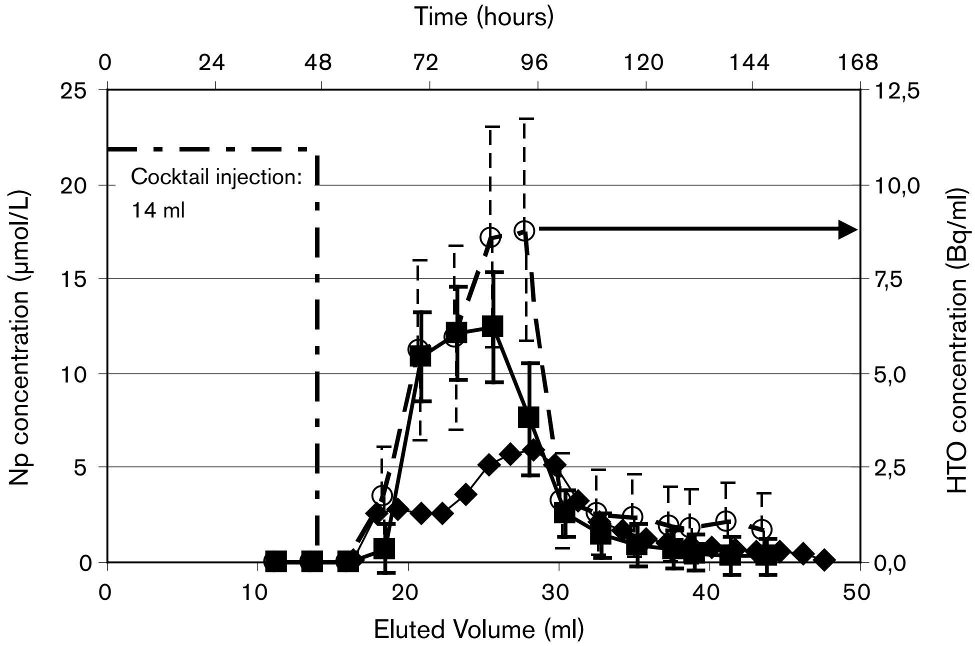


Figure 2-14. Measured breakthrough of Np and HTO. Labels: Squares – Np in CHEMLAB 2 experiment, Diamonds – Np in laboratory experiment, Circles – HTO in CHEMLAB 2 experiments.

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

The third actinide experiment in Äspö HRL was started at the end of 2002 and is still under completion due to several technical problems with CHEMLAB 2.

The following conclusions can be drawn from the results of the actinide migration experiments in laboratory and CHEMLAB 2:

- The design of the drill cores enclosed in stainless steel autoclaves, tubings and fittings, as well as the sampling procedure, fit excellently with the demands for laboratory and *in situ* experiments.
- The migration experiments performed at the laboratory and in the CHEMLAB 2 probe complemented each other. The CO_2 partial pressure adjusted in the laboratory resulted in the same actinide speciation as expected under *in situ* conditions.
- Abraded material gained by cutting of the two cores was analysed with respect to the actinide concentrations by ICP-MS. Even in the case of pulse injection of actinides (experiments with Core #1), it was possible to determine the sorbed actinides.
- All migration experiments resulted in a breakthrough of Np(V) only. In all cases, the recovery of Np was ≤ 40%. Breakthrough of Am(III) and Pu(IV) was not detected in the effluent. The lower limits of the retardation factors (defined as the ratio of groundwater flow velocity to the velocity of the tracer) for both Am and Pu were calculated to be 135.

- Improved analytical methods, such as laser ablation techniques and micro α-radiography show similar distribution for Np and Am. Data from both laboratory and *in situ* tests indicate that sorption is not primarily attributed to different sorption processes or properties along the flow path, but more to its local geometric properties and the available surface areas.
- By TTA (thenoyltrifluoroacetone) extraction of Np dissolved with a non oxidising acid from some slices it could be shown that Np(V) undergoes reduction to Np(IV) during sorption.

Modelling of the actinide migration and the correlation of observed batch sorption data with the results of migration experiments are in progress.

2.5 Colloid Project

2.5.1 Background

Colloids are small particles in the size range 10^{-6} to 10^{-3} mm. The colloidal particles are of interest for the safety of a repository for spent nuclear fuel because of their potential to transport radionuclides from a defect waste canister to the biosphere. SKB has for more than 10 years conducted field measurements of colloids. The outcome of those studies performed nationally and internationally concluded that the colloids in the Swedish granitic bedrock consist mainly of clay, silica and iron hydroxide particles and that the mean concentration is around 20–45 ppb which is considered to be a low value /Laaksoharju et al, 1995/. The low colloid concentration is controlled by the attachment to the rock, which reduces both the stability of the colloids and their mobility in aquifers.

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

The findings of potential transport of solutes by colloids and access to more sensitive instruments for colloid measurements motivated a Colloid Project at Äspö HRL The project was initiated by SKB in 2000 and is planed to continue until the end of 2006.

2.5.2 Objectives

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

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

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

2.5.3 Experimental concept

The Colloid Project comprises laboratory experiments as well as field experiments. The latter include background measurements, borehole specific measurements and fracture specific measurements.

Laboratory experiments

The role of the bentonite clay as a source for colloid generation at varying groundwater salinity (NaCl/CaCl) was studied in laboratory experiments. Bentonite clay particles were dispersed in water solutions with different salinity and the degree of sedimentation was studied. The experiment investigated in detail the chemical changes, size distribution and the effects from Na versus Ca rich bentonite associated with colloid generation /Wold and Eriksen, 2002a; Karnland, 2002/.

Background measurements

The natural background colloid concentrations were measured from 8 different boreholes, representing groundwater with different ionic strength, along the Äspö HRL-tunnel, see Figure 2-15.

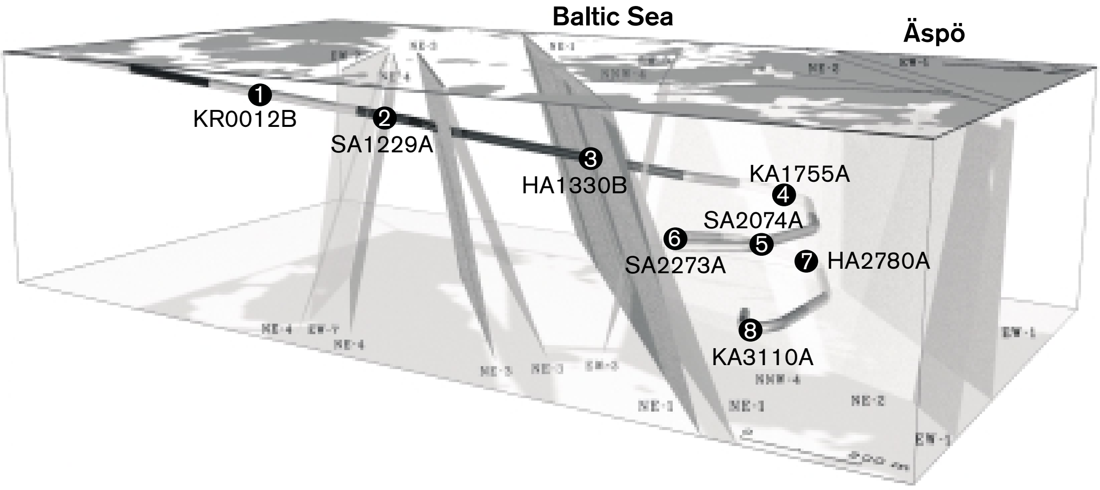


Figure 2-15. The 8 boreholes sampled for colloids along the Äspö tunnel.

The colloid content is measured on-line from the boreholes by using a modified laser based equipment LIBD (Laser-Induced Breakdown-Detection) which has been developed by INE in Germany, see Figure 2-16. The advantage is that the resolution of this equipment is higher compared with standard equipments. It is therefore possible to detect the colloid content at much lower concentrations than previously possible /Hauser et al, 2002/. The outcome of these measurements was compared with standard type of measurements such as particle counting by using Laser Light Scattering (LLS) on pressurised groundwater samples /Wold and Eriksen, 2002a/. Standard type of filtration and ultra filtration was performed on-line/at-line of the boreholes /Wold and Eriksen, 2002b; Vuorinen, 2002/. In addition, samples for groundwater /Mattsén, 2002; Rantanen and Mäntynen, 2002/, microbes /Pedersen, 2002a/ and humic material /Buckau and Wolf, 2002/ were collected from the selected boreholes in order to judge the contribution from these on the measured colloid concentration. The electrical conductivity was measured along the tunnel from water venues in order to reflect the variability of the groundwater composition which can affect the colloid stability /Gurban, 2002/.

The results from the background measurements indicate that the natural colloid content is decreasing with groundwater salinity and depth, see Figure 2-17. Natural colloidal particles consist of organics, inorganic colloids (clay, calcite, ironhydroxide) and of microbes. The microbe content is increasing with the content of organic carbon. Microbes form few but large particles, organic particles are small but can have a high concentration. The concentration is decreasing with depth and salinity. The colloid content at Äspö is less than 300 ppb and at repository level it is less than 50 ppb /Laaksoharju et al, 1995; Degueldre, 2002; Hauser et al, 2002; Wold and Eriksen, 2002a; Vuorinen, 2002; Gurban, 2002; Wold and Eriksen, 2002b; Mattsén, 2002; Rantanen and Mäntynen, 2002; Pedersen, 2002a/.

Figure 2-16. *Equipment for Lacer-Induced Breakdown-Detection (LIBD) of colloids. The equipment is installed in a van in order to allow mobility and on-line measurements.*

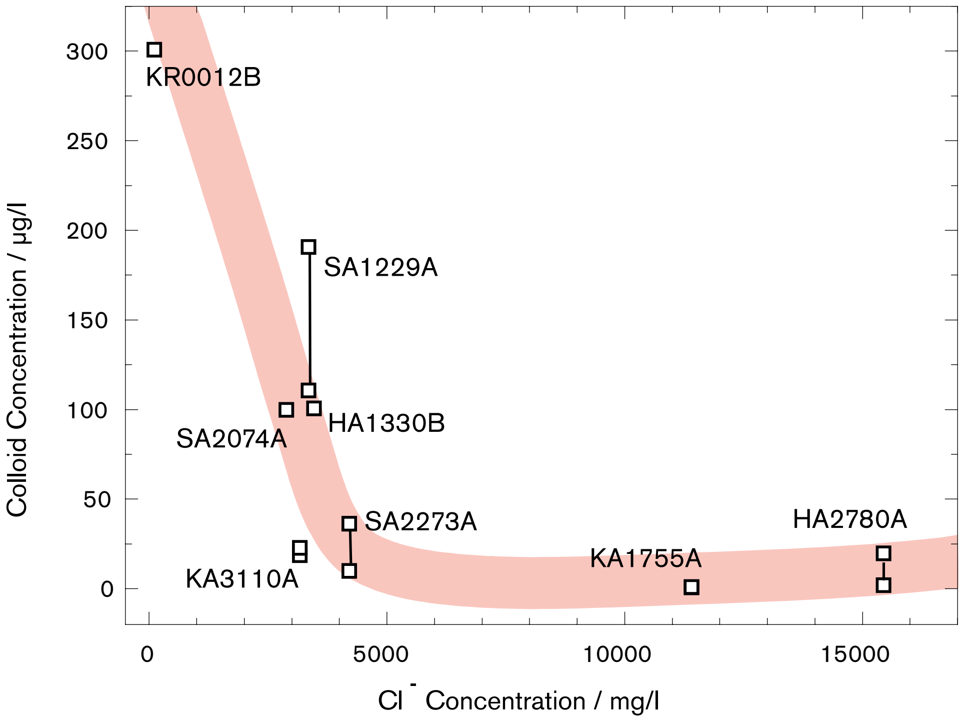


Figure 2-17. *The natural colloid concentration is decreasing with groundwater salinity but also with depth at Äspö HRL /Hauser et al, 2002/.*

Borehole specific measurements

The aim of the experiment is to determine the colloid generation properties of the bentonite clay in contact with the prevailing groundwater conditions at Äspö. For this purpose laboratory test were carried out in order to optimise the "colloid reactor" (filter textile with bentonite clay) design. For the borehole specific measurements 4 boreholes along the Äspö tunnel and 2 boreholes at Olkiluoto in Finland will be investigated. The boreholes are selected so the natural variation in the groundwater composition at Fennoscandia is covered. The groundwater is in contact with the bentonite clay adapted in a container/packer equipment in the borehole and the colloid content is measured prior and after in contact with the bentonite clay, see Figure 2-18. The colloid content is measured by using conventional filtering and ultra filtration.

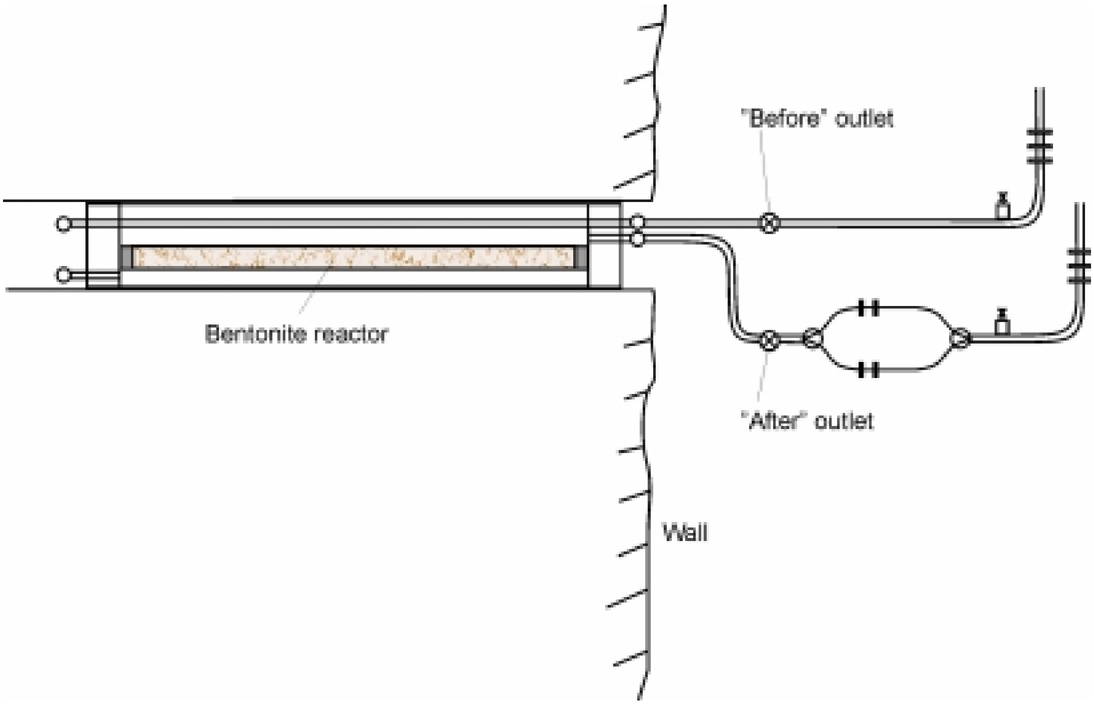


Figure 2-18. The natural groundwater is in contact with the bentonite clay surrounded by a filter textile. The water flowing by the reactor is sampled and analysed. A bypass allows colloid determination of the natural groundwater. The aim is to determine the colloid generation potential from the bentonite in contact with the water.

Fracture specific experiment

A fracture specific measurement is planned within the Colloid Project during the time period 2003–2006. According to present plans two nearby boreholes intersecting the same fracture having the same basic geological properties will be selected for the fracture specific experiment at Äspö HRL. One of the boreholes will be used as an injection borehole and the downstream borehole will be used for monitoring. After assessing the natural colloid content in the groundwater, bentonite clay will be dissolved in ultra pure water to form colloidal particles. The colloids are labelled with a lanthanide (e.g. Europium) and the fluid is labelled with a water conservative tracer. The mixture will be injected into the injection borehole, see Figure 2-19. The colloidal content will be measured with laser (LIBD/LLS), the water is filtered and the amount of tracers is measured. The result of major interest is the changes in colloid content prior and after the transport through the fracture. The outcome of the experiment will be used to check performed model calculations and to develop future colloid transport modelling.

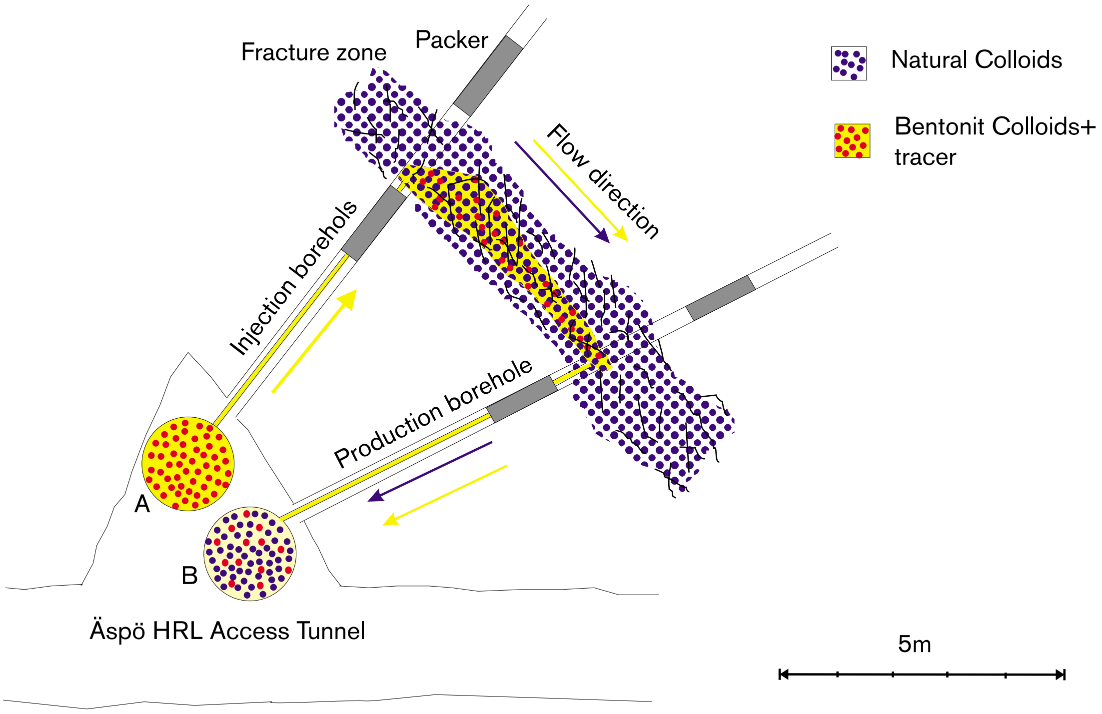


***Figure 2-19.** Fracture specific measurement – injection of bentonite colloids and monitoring of the injected and natural colloids in the production borehole.*

2.5.4 Results

The following topics have been carried out:

- Laboratory tests January 2001 – March, 2002.
- Field measurements, background colloid content October 2001 – March 2002.
- International Äspö Colloid workshop was held in March 2002 in Stockholm.
- Laboratory test concerning the design and optimisation of the colloid reactors April 2002 – December 2002.

The major results from the laboratory experiments are that dissolution of bentonite is dependent of the background electrolyte and its concentration. In low ionic strength of Na^+ the osmotic pressure is high which results in a loose gel structure in the bentonite. Colloids can form and migrate out in the solution. The dissolution of bentonite is very slow at pH 8 to 8.5 at 20°C, but increases with temperature and when changing pH to < 8 or > 8.5.

The major finding from the background colloid measurements at Äspö HRL is that, despite different techniques and sometimes large uncertainties in the measurements, the colloid content at repository depth is in the order of ppb. These results support the earlier measurements and modelling of colloid content which indicated low colloid concentrations in deep groundwaters at Äspö.

The following conclusions can be drawn:

- The dissolution of bentonite and hence the colloid formation is dependent on background electrolyte and its concentration.
- Natural colloidal particles consist of organics, inorganics (clay, calcite, iron hydroxide) and microbes.
- Microbes form few but large particles, whereas organic particles are small but can be many.
- Microbe content is increasing with the content of organic carbon.
- The colloid concentration is decreasing with depth and salinity.
- The colloid content at Äspö is less than 300 ppb.
- The colloid content at repository level is less than 50 ppb.
- The groundwater variability obtained in the sampled boreholes reflects well the natural groundwater variability along the whole HRL tunnel.

2.6 Microbe Project

2.6.1 Background

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future deep repository for spent fuel /Pedersen, 2002b/. The study of microbial processes in the laboratory gives valuable contributions to our knowledge about microbial processes in repository environments. However, the concepts suggested by laboratory studies must be tested in a repository like environment. The reasons are several. Firstly, at repository depth, the hydrostatic pressure reaches close to 50 bars, a setting that is very difficult to reproduce in the microbiology laboratory. The high pressure will influence chemical equilibria and the content of dissolved gases. Secondly, the geochemical environment of deep groundwater, on which microbial life depends, is complex. Dissolved salts and trace elements, and particularly the redox chemistry and the carbonate system are characteristics that are very difficult to mimic in a university laboratory. Thirdly, natural ecosystems, such as those in deep groundwater, are composed of a large number of different species in various mixes /Pedersen, 2001/. The university laboratory is best suited for studies on pure cultures and, therefore, the effect from consortia of many participating species in natural ecosystems cannot easily be investigated there.

The limitations of university laboratory investigations arrayed above have resulted in the construction and set-up of sites for microbiological investigations in the Äspö HRL tunnel. The main site is the MICROBE laboratory at the 450-m level, but two more sites along the A-side of the tunnel have been in use during 2002, i.e. at 907 and 2200-m tunnel length. A third site at the B-side of the tunnel at 1127-m tunnel length will possibly be in use during 2003. Three specific microbial process areas have been studied at the MICROBE sites during 2002. They are: Bio-immobilisation of radionuclides, Microbial effects on the chemical stability of deep groundwater environments, and Microbial corrosion of copper.

Bio-immobilisation of radionuclides

A large group of microbes catalyse the formation of iron oxides from dissolved ferrous iron in groundwater that reaches an oxidising environment /Ferris et al, 1999, 2000/. Such biological iron oxide systems (BIOS) will have a retardation effect on many radionuclides. Typically, microbes form stalks and sheaths that increase the volume of the iron oxides from densely packed inorganic oxides to a fluffy, rust-like material with water contents of up to 99%. The microbes contribute to the exposure of a large oxide area to trace elements flowing by with the groundwater and the organic biological material adds a strong retention capacity in addition to iron oxides. The retention effect from BIOS has been studied at the site at 2200 m tunnel length.

Microbial effects on the chemical stability of deep groundwater environments

Microorganisms can have an important influence on the chemical situation in groundwater /Haveman and Pedersen, 2002/. Especially, they may execute reactions that stabilise the redox potential in groundwater at a low and, therefore, beneficial level for the repository. It is hypothesised that hydrogen from deep geological processes contributes to the redox stability of deep groundwater via microbial turnover of this gas. Hydrogen, and possibly also carbon monoxide and methane energy metabolisms will generate secondary metabolites such as ferrous iron, sulphide and organic carbon. These species buffer towards a low redox potential and they will act reducing on possibly introduced oxygen. A circulation system, and analytical instrumentation for dissolved gas in groundwater have been developed during 2002 and microbial bio-films have been grown under *in situ* conditions at the MICROBE 450-m site.

Microbial corrosion of copper

Bio-corrosion of the copper canisters, if any, can be the result of microbial sulphide production. Two important questions have been identified and studied: Can sulphide-producing microbes survive and produce sulphide in the bentonite surrounding the canisters? Can microbial sulphide production in the surrounding rock exceed a performance safety limit? A series of laboratory and field experiments have indicated that this is not the case /Pedersen et al, 2000a,b/. However, the results have been criticised for not accounting for natural conditions such as high pressure and the natural population of sulphate reducing bacteria in deep groundwater. This issue has been addressed at the MICROBE 450-m site.

2.6.2 Objectives

The major objectives for the MICROBE sites are:

- To provide *in situ* conditions for the study of bio-mobilisation of radionuclides (not executed during 2002).
- To present a range of conditions relevant for the study of bio-immobilisation of radionuclides.
- To offer proper circumstances for research on the effect of microbial activity on the long-term chemical stability of the repository environment.
- To enable investigations of bio-corrosion of copper under conditions relevant for a deep repository for spent fuel.

2.6.3 Experimental concept

Three sites along the tunnel have been in operation during 2002. The main site has been the MICROBE 450-m underground laboratory. This is where the research efforts were being focussed. Some tasks required settings that could not be achieved at the 450-m site. Therefore, two additional sites were employed along the tunnel.

The MICROBE 450-m site

The main MICROBE site is on the 450 m level in the F-tunnel. A laboratory container has been installed with laboratory benches, an anaerobic gas box and an advanced climate control system, see Figure 2-20. Three core drilled boreholes, KJ0050F01, KJ0052F01 and KJ0052F03, intersecting water conducting fractures at 12.7, 43.5 and 9.3 m, respectively, are connected to the MICROBE laboratory via 1/8" PEEK tubing. The boreholes are equipped with metal free packer systems that allow controlled circulation of groundwater via respective fracture /Pedersen, 2000/. Each borehole has been equipped with a circulation system (Figure 2-21) offering a total of 500 cm^2 of test surface in each circulation flow cell set up for biofilm formation at *in situ* pressure, temperature and chemistry conditions. The systems operate at the pressures 24, 32 and 24 bars in KJ0050F01, KJ0052F01 and KJ0052F03, respectively. The flow through the flow cells is adjusted to about 15 ml per minute, which corresponds to a flow rate over the surfaces of 0.5 mm per second. Temperature is controlled and kept close to the *in situ* temperature at around 15–16°C. Remote alarms have been installed for high/low pressure, flow rate and temperature.

Figure 2-20. *The Microbiology Laboratory environment at the MICROBE 450-m site is equipped with three circulation systems (right), an anaerobic box (forward), an* in situ *gas extractor and a Kappa 5 gas chromatograph (right of the anaerobic box).*

Figure 2-21. *One of the circulating systems at the MICROBE 450-m site, built in a refrigerator equipped with a fan that ensures even temperature distribution. Four flow cells offers 125 cm^2 surface each for attachment and growth of microbes. The cells have a stainless steel outer shell, but expose only Polyvinyldifluorid plastic inside (PVDF) to the flowing groundwater. A pump on top inside the cabinet, with a pump rate control on the top outside, circulates groundwater from the borehole via the flow cells and back into the aquifer. A flow meter at the bottom registers flow rate and pumped volume over time.*

The BIOS site at 2200-m tunnel length and the 907-m ditch

Organic surfaces and iron oxides have been identified as important factors in radionuclide transport modelling. Several microorganisms oxidise ferrous iron to ferric iron resulting in a mix of organic material (microbes) and iron oxides, here denoted BIOS (Biological Iron Oxide Systems). BIOS can be found everywhere along the Äspö HRL tunnel system. This BIOS is mainly produced by the stalk-forming bacterium *Gallionella ferruginea* /Hallbeck and Pedersen 1990, 1991, 1995; Hallbeck et al, 1993/. One particularly good site for investigations has been identified at tunnel length 2200-m, on the A side. A vault is reaching about 10 m into the host rock perpendicular to the tunnel and it has a borehole in the front that delivers groundwater rich in ferrous iron and iron oxidising bacteria. The borehole has been connected to two 200 x 30 x 20 cm artificial channels that mimic ditches in the tunnel. The channels have rock and artificial plastic support that stimulate BIOS formation, see Figure 2-22. Retention of naturally occurring trace elements in the groundwater by the BIOS was investigated.

Figure 2-22. *Biofilms of the stalk forming bacterium Gallionella ferruginea developed after five weeks on the plastic walls of the outlet channel chamber (20 x 20 cm) at the 2200-m BIOS site. The fluffy character of the BIOS offers a huge surface area for trace element sorption. The material on the walls mainly consists of microbial cells, stalks and metal oxides.*

At 907-m tunnel length, on the A-side, a small vault with a rescue chamber supports a ditch with groundwater that is rich in ferrous oxides and iron oxidising bacteria (Figure 2-23). This ditch was used as a natural analogue to the artificial BIOS channels at 2200-m. Growth characteristics of the BIOS were compared between the two sites.

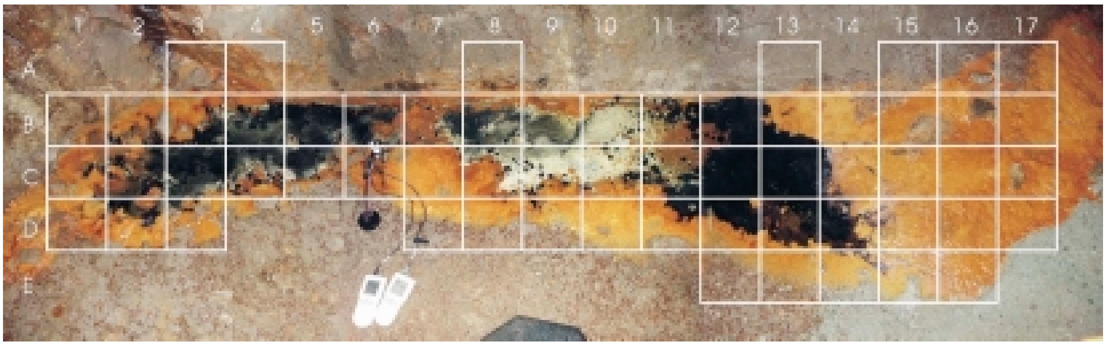


Figure 2-23. *The 907-m ditch site is characterised by a shallow, elongated water pond that overflows into the main tunnel ditch to the right in the image. Brown material is BIOS. The black colour is from iron sulphide precipitates and the white material is calcium carbonate. The overlaid grid created an organised environment and enabled pH, oxygen and redox measurements in three dimensions (Figure 2-24). Field instruments are shown in the bottom of the figure. Grid size is about 25 x 25 cm.*

2.6.4 Results

Bio-immobilisation of radionuclides

It was regarded important to understand the conditions under which BIOS develop and prosper. Therefore, the optimal growth conditions for BIOS were determined using pH, redox and oxygen electrodes (Radiometer). The ditch site at 907-m and the BRICs at 2200-m were investigated in detail. Measurements of the redox potential (Eh), oxygen concentration and the pH were performed in a three-dimensional grid pattern and the presence or absence of BIOS at the measurement spots were noted. The data obtained then cover distribution and variation of the three measured parameters and BIOS in length, width and depth of the investigated sites. Figure 2-24 shows the results from those measurements. Three Eh/oxygen zones were detected. No growth could be detected at oxygen concentrations lower than 0.2 mg oxygen/ml and at Eh below 125 mV.

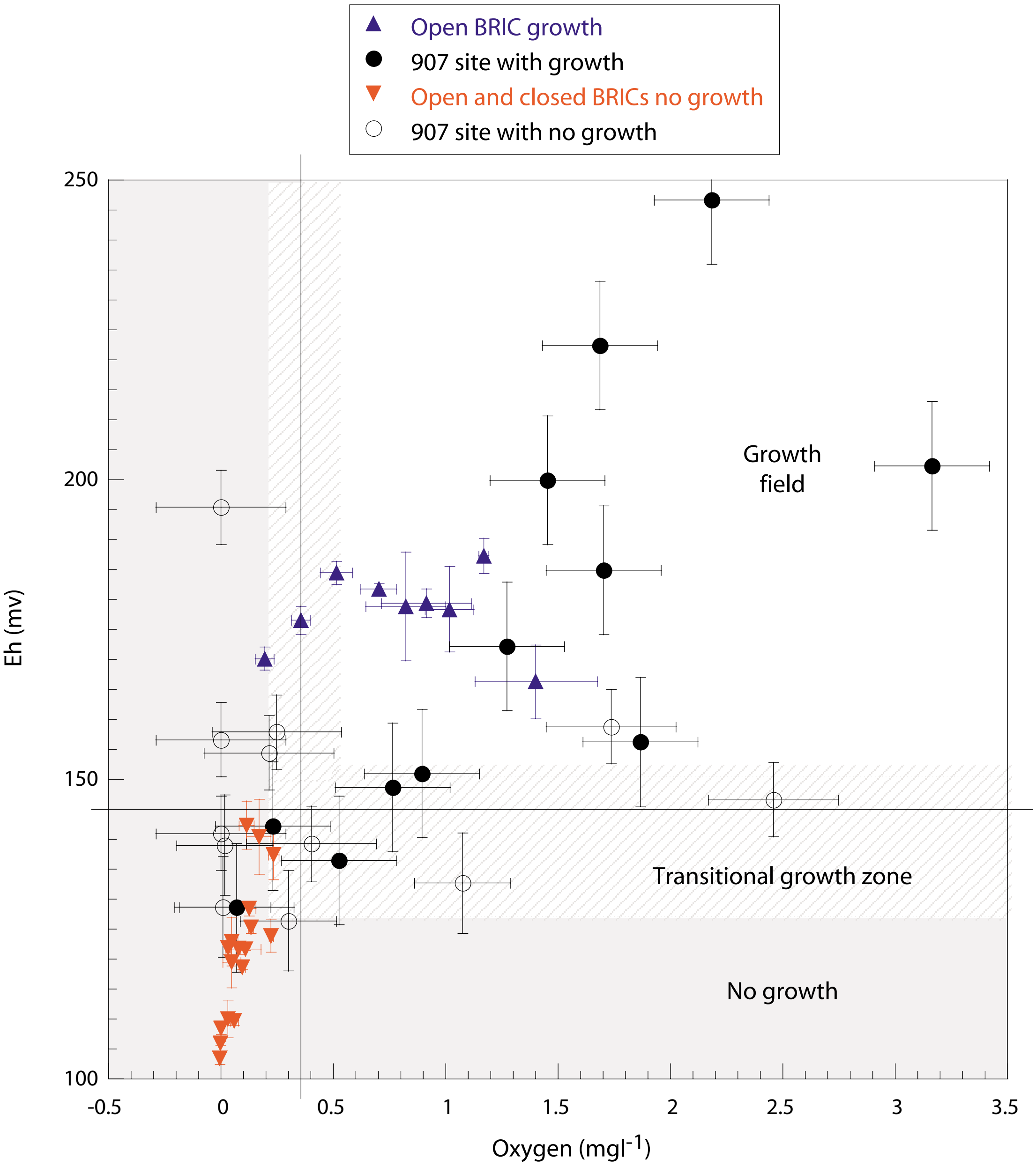


Figure 2-24. REDOX and oxygen measurements correlated with the presence of BIOS at the 907-m and 2200-m tunnel sites. Data were obtained in a three dimensional pattern comprising length, width and depth of the 907-m ditch and the BRICs.

A transient zone with none to moderate growth was found between the oxygen interval 0.2 to 0.5 mg oxygen/ml and the Eh interval 125 to 150 mV. Significant or massive growth was registered in the BRICs within 0.2 to 1.4 mg oxygen/ml and 165 to 190 mV. The 907-m ditch had a much more dispersed distribution, ranging within the intervals 0.1 to 3.2 mg oxygen/ml and 125 to 250 mV. The results clearly demonstrated the strong advantage with the BRICs versus a natural ditch in the tunnel. The BRCIs offered very concise data that were well centred around the average, while the ditch delivered a rather scattered data set. It can safely be concluded that the BRICs offer a stable and reproducible environment for further studies of trace element retention, and that the first data obtained (Figure 2-25) are significant.

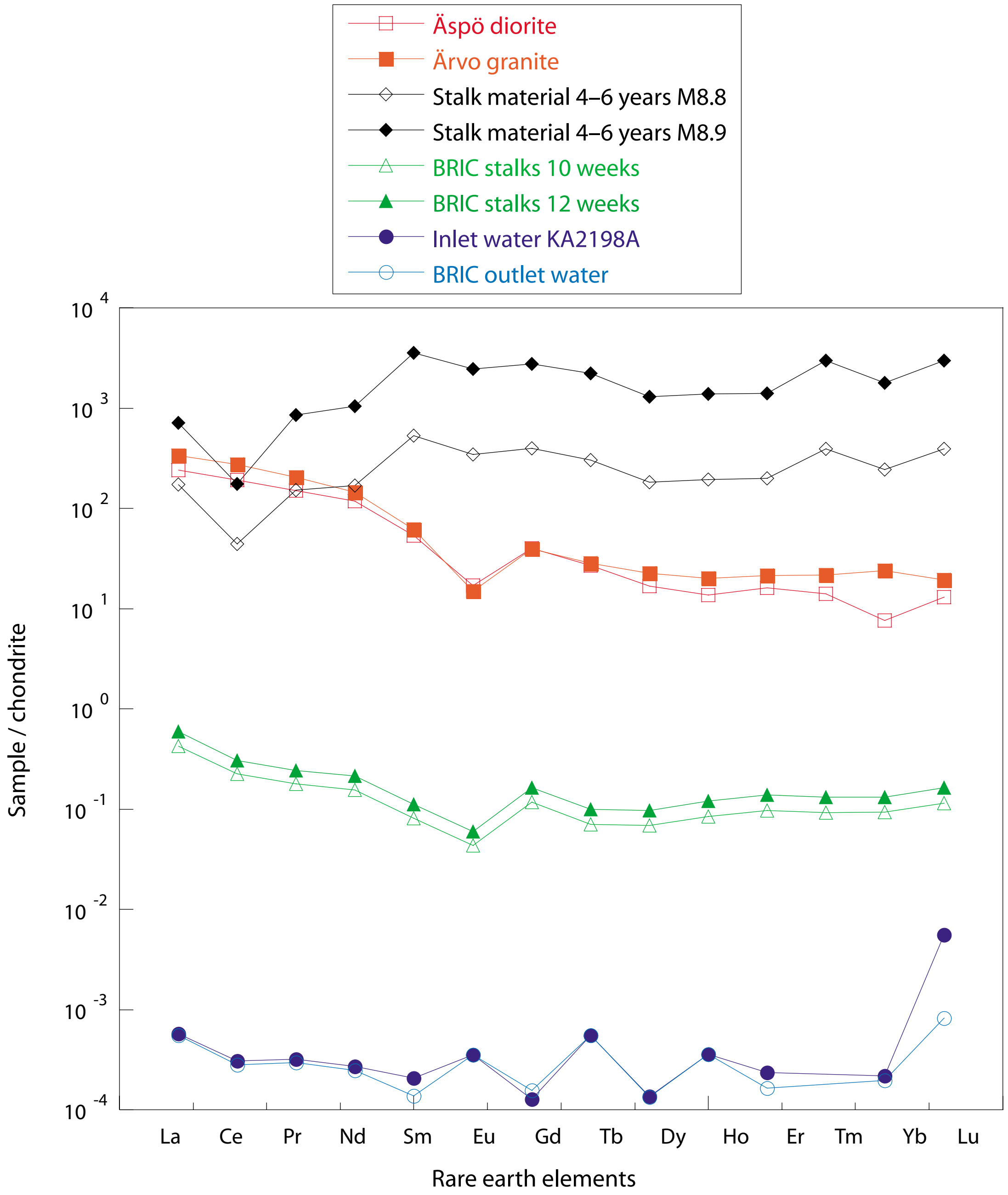


__Figure 2-25.__ Rare earth element sorption on BIOS with different age in comparison with the concentrations in groundwater and Äspö/Ävrö rock material. The data have been normalised to chondrite.

BIOS from different sites and with varying age were analysed for the content of rare earth elements (REE), see Figure 2-25. The results showed that the REE concentration analysed in the inflow and outflow of the BRICs were more than 1000 times lower compared to a chondrite standard. Ten to twelve weeks old BIOS in the BRICs adsorbed three orders of degree more REE compared to the groundwater. Very old BIOS (4–6 years), collected at 1127B-m tunnel length had a REE concentration that were about one million higher compared to the groundwater and 10 to 100 times higher than what is found in typical Äspö/Ävrö rock material. The obtained data clearly demonstrates the excellent REE sorption capacity of BIOS, as first suggested by /Ferris et al, 1999, 2000/.

Microbial effects on the chemical stability

The work during 2002 has focussed on the set up of the laboratory container, a climate control system and analytical instrumentation and procedures. The laboratory is now well equipped with laboratory benches and an anaerobic box for work with oxygen sensitive organisms and trace elements (Figure 2-20). The gas chromatograph installed can analyse hydrogen and carbon dioxide at a ppb detection level and methane, carbon dioxide, ethane, and ethene at a ppm detection level. Gas chromatographs are sensitive instruments, and this particular one is sensitive to changes in the environmental temperature. Therefore, an advanced climate control system has been installed that keeps the temperature in the laboratory at a stable level during analysis. The extraction of gases from groundwater is difficult. During 2002, we have constructed and built a gas extractor that removes gas from pressurised groundwater and measures the extracted gas volume (Figure 2-20). The gas can be diluted with nitrogen and injected in the gas chromatograph. Extraction, dilution and injection are all performed in one line without exposing the gas or the groundwater to the atmospheric environment in the laboratory. The system works excellent and is ready for operation during 2003 and onwards. Figure 2-26 shows the result from a dilution and analysis experiment of calibration gas. Linearity and reproducibility are very good.

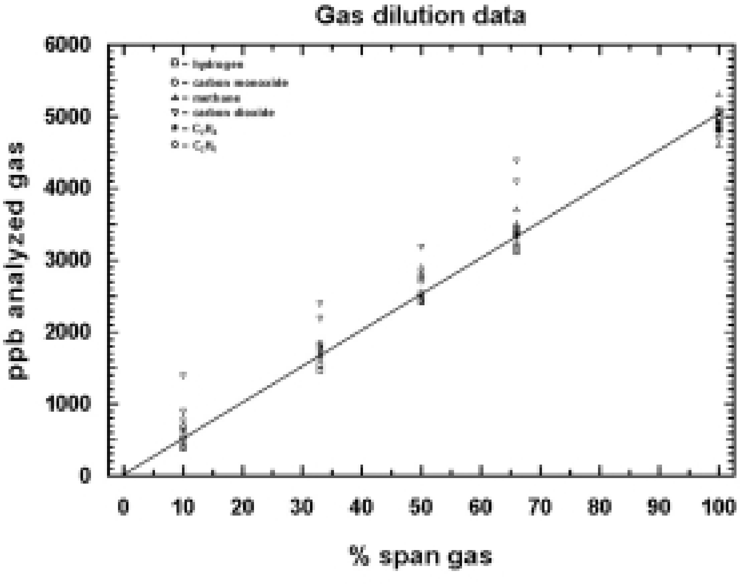


Figure 2-26. *A calibration gas mix with about 5 ppm of each span gas, hydrogen, carbon monoxide, methane, ethane, and ethane were diluted in nitrogen and injected with the gas extractor (Figure 2-20).*

The circulation systems (Figure 2-21) have been circulating groundwater from the packed of fractures since 2 July 2002. Microbial bio-films developed relatively quickly. After 80 days, bio-films with about $6.5 \cdot 10^6$ cells per cm^2 had developed (Figure 2-27). The three different circulations developed different bio-films as judged from cell morphology. In conclusion, the circulation systems are now up and running and ready for a series of different experiments that will start during 2003. They comprise microbial processes influencing redox and chemical stability of groundwater, radionuclide bio-immobilisation and bio-mobilisation experiments and also work on the general structure and microbial ecology of deep microbial ecosystems.

Microbial corrosion of copper

The Swedish spent fuel will be encapsulated in copper canisters, placed in tunnels at a depth of 500 m in hard rock and surrounded by compacted bentonite clay. A critical function in the repository is the integrity of the copper canister as the canister acts as a barrier for radionuclide dispersal in the groundwater. One possible threat to the copper canister integrity in the repository is microbial induced corrosion (MIC). Hydrogen sulphide produced by sulphate reducing bacteria (SRB) can corrode copper. The environment in a deep repository will be extreme for micro-organisms due to high temperature, high radiation levels, high pH, low water activity and low levels of organic carbon.

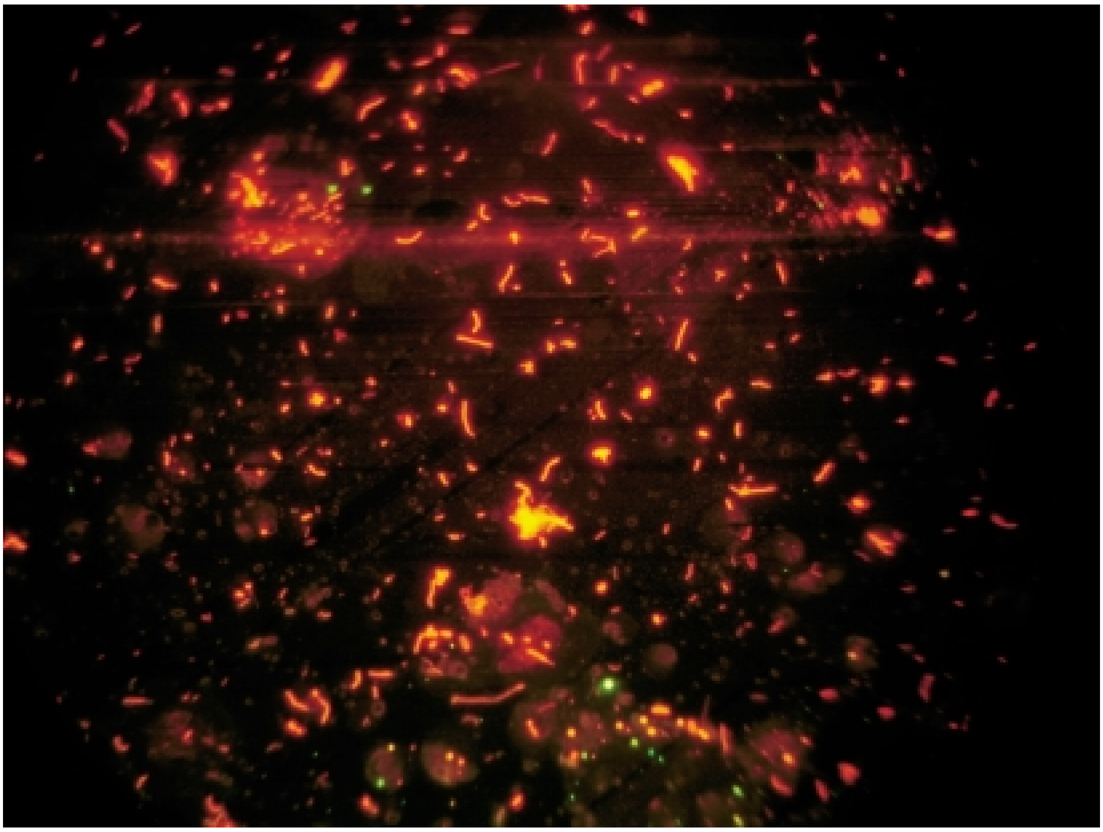


Figure 2-27. *Attached micro-organisms on glass surfaces exposed to slowly flowing groundwater from KJ0050F01 during 80 days. The micro-organisms are stained with acridine orange, which gives them an orange glow when illuminated with blue light in the microscope, so called epi-fluorescence microscopy. The size of the microbes in the bio-film centres around 1 micrometer.*

We have investigated activity of SRB in compacted bentonite with densities of 1.5, 1.8, 2.0 g/cm^3 using stainless steel odometers with $^{35}SO_4$ as the main sulphur source for the SRB. The investigations were performed under *in situ* conditions at the MICROBE 450-m site. Canister type copper plates were placed down in the odometers, either with the top end in contact with the added groundwater or with 3–4 mm bentonite between the end and the added groundwater (Figure 2-28). The experiments were executed in the anaerobic box (Figure 2-20) with direct connection to groundwater from KJ0052F03. This borehole has a demonstrated natural population of SRB /Pedersen, 2000/. Radioactive hydrogen sulphide formed by the SRB reacts with the copper and form radioactive copper sulphide, which was measured by electronic radiography using an Instant Image Microautoradiography instrument (Packard). A similar set-up with groundwater sterilised through a 0.2 µm filter was used as control. Here, we found that SRB were active and produced hydrogen sulphide during the initial phase of bentonite swelling. The activity of the SRB could be correlated with the final density of the bentonite, the highest density having the lowest overall SRB activity (Figure 2-29). We also demonstrated, that SRB need not to be introduced into the bentonite from groundwater. We found SRB that are present in a dormant state in the commercial MX-80 bentonite. These dormant SRB become activated by addition of water and start to produce hydrogen sulphide.

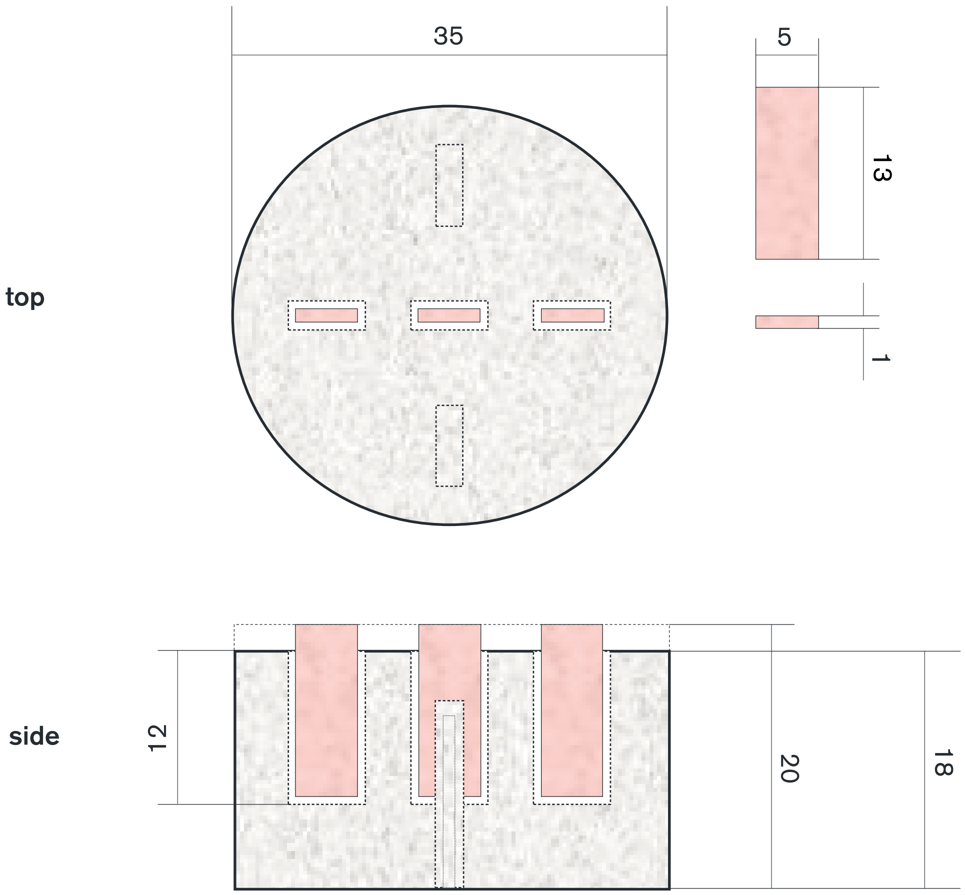


Figure 2-28. *The experimental configuration of the sulphide corrosion test. Copper plates were installed in bentonite compacted to different densities. Three copper plates were installed from above and two copper plates from below. Above is the side of the bentonite in the odometer that was connected directly to groundwater from KJ0052F03. The* in situ *pressure, 24 bars, was applied on the bentonite throughout the incubation period. All distances are in millimetres.*

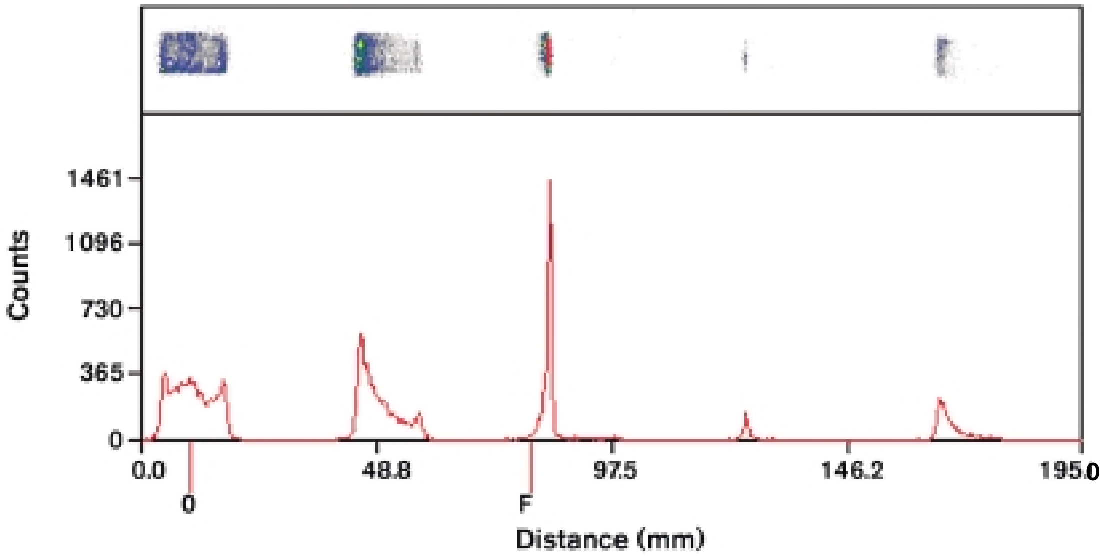


Figure 2-29. *Example of a typical result from the ^{35}S copper corrosion experiment with in situ populations of sulphate reducing bacteria (SRB). The figure shows radioactivity profiles along one surface of the plates as counts (lower diagram part) and as a colour graded map (upper diagram part). The plates are from left to right: 1.5, 1.8, and 2.0 g/cm^3, all with groundwater SRB, 1.8 and 2.0 g/cm^3 both with natural bentonite and with sterile groundwater. Distance is in millimetres and counts are disintegrations per minute on each measured spot. The spot size is 0.4 x 0.4 mm. (Ignore O and F designations).*

2.7 Matrix Fluid Chemistry

2.7.1 Background

Knowledge of matrix fluids (i.e. accessible interconnected pore space fluid/water) and groundwaters from crystalline rocks of low hydraulic conductivity ($K< 10^{-10}$ ms^{-1}) will complement the hydrogeochemical studies already conducted at Äspö, for example, matrix fluids are suspected to contribute significantly to the salinity of deep formation groundwaters. Small-scale fractures and fissures ($K= 10^{-10}–10^{-9}$ ms^{-1}) will facilitate the migration of matrix fluids through the rock matrix. By mixing and in- and out-diffusion processes the matrix fluid chemistry will become closely related to the chemistry of groundwaters present in these hydraulically conducting minor fractures. This is important for 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.

The experimental part of the experiment is now completed and the onus during 2002 has been on final reporting.

2.7.2 Objectives

The main objectives of the Matrix Fluid Chemistry Experiment were to:

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

2.7.3 Experimental concept

The Matrix Fluid Chemistry experiments comprised:

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

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

Special equipment, see Figure 2-30, was designed to sample the matrix pore space fluids/groundwaters ensuring: (a) an anaerobic environment, (b) minimal contamination from the installation, (c) minimal dead space in the sample section, (d) the possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock, (e) in-line monitoring of electrical conductivity and drilling water content, (f) the collection of fluids (and gases) under pressure, and (g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

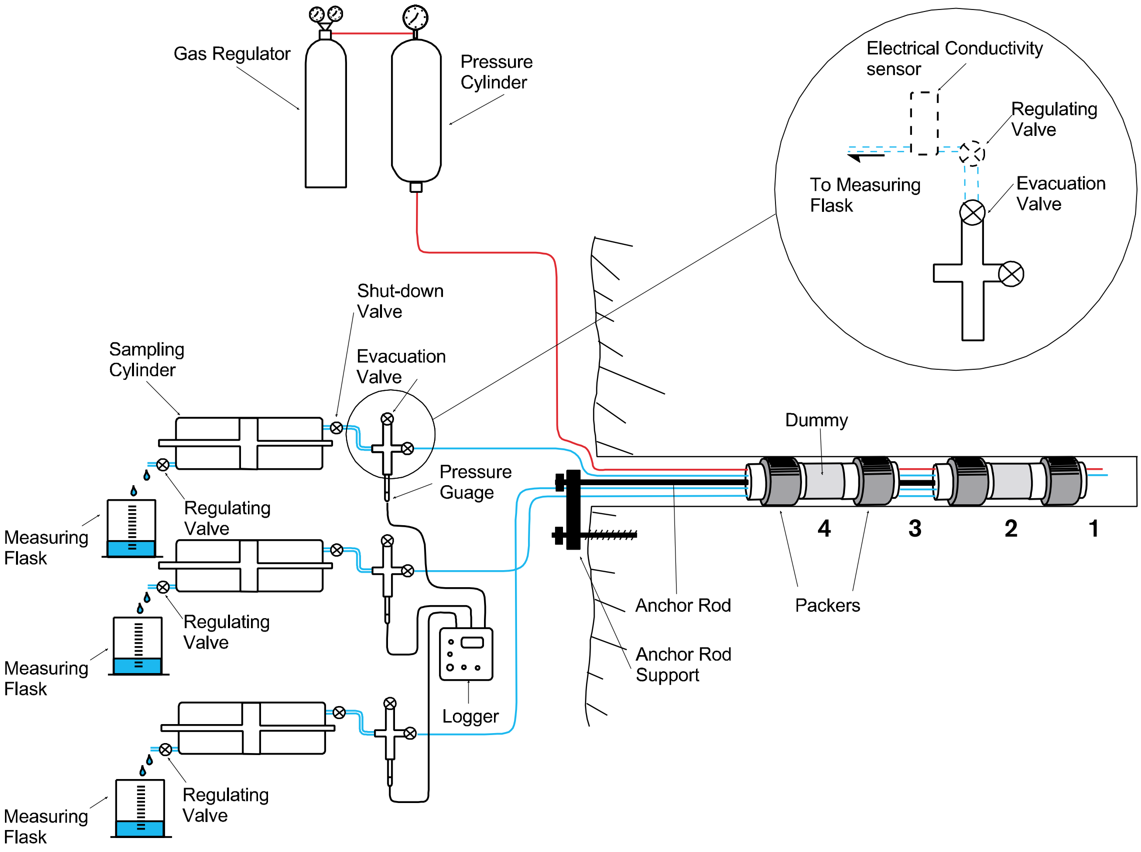


Figure 2-30. Matrix Fluid Chemistry experimental set-up. Borehole sections 2 and 4 were selected to collect matrix fluid; sections 1–4 are continuously monitored for pressure.

2.7.4 Results

The major data resulting from the Matrix Fluid Chemistry experiment were available by the end of 2001 and the main onus of 2002 was to complete interpretation and reporting of the results. At the end of 2002 almost all of the data were reported as Technical Documents, or at least a good draft was available; this included two major Synthesis Reports. In addition, a first draft of the Final Report was produced. The Final Report is expected to be completed for publication in June 2003.

The main results from the Matrix Fluid Chemistry experiment are:

- Interconnected pore space groundwaters and gases were successfully sampled on several occasions from the rock matrix ($T= 10^{-14}–10^{-12}$ m^2s) from 3–4 of the isolated borehole sections.
- The sampled waters consisted dominantly of groundwaters of similar chemistry to more transmissive fractures ($T= 10^{-9}–10^{-7}$ m^2s) in the surrounding bedrock environment. This was supported by the type and content of the gases obtained.
- There was some evidence of drawdown effects influencing the rock matrix resulting from the tunnel construction (i.e. during a 10–15 year timescale).
- There was little evidence that the salinity of the matrix groundwaters had been influenced significantly by fluid inclusions restricted mainly to quartz hosts.

- Some tectonic rupturing of fluid inclusions was apparent but these tend to be close to grain boundaries and are commonly characterised by low salinity and gas contents.
- Some trace elements and isotopes in the sampled groundwaters suggested restricted input from matrix pore space fluids.
- It is proposed that the interconnected pore space groundwaters have entered the borehole sections via a relatively “open” rock fabric comprising an interconnected system of micro-fractures.
- Groundwater movement through the rock matrix has been the result of diffusion and advective processes and that these advective processes may have been enhanced recently by differential hydraulic gradients set up between the rock matrix and: (a) the open borehole sections, and (b) the evacuated tunnel.
- However, predictions of groundwater flow times to the borehole sections during pre-HRL undisturbed hydraulic conditions are in accordance with the estimated hydraulic conductivity and the measured porosity.
- Äspö appears to be unique in that the highly permeable bedrock (at both large- and small-scales) has facilitated the continuous removal and replacement of the interconnected pore space groundwaters over relatively short periods of geological time, probably hundreds to a few thousands of years. Other less permeable crystalline rock sites might therefore be expected to take a much longer time (tens of thousands of years or much more) to achieve a similar result. Consequently, because of such long residence timescales the pore space fluids may be expected to become highly saline in type from water/rock interactions.

2.8 Modelling of Groundwater Flow and Transport of Solutes

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

Background

The work within Äspö Task Force constitutes an important part of the international co-operation within the Äspö HRL. The group was initiated by SKB in 1992 and is a forum for the organisations to interact in the area of conceptual and numerical modelling of groundwater flow and transport. Seven organisations (see Chapter 5) in addition to SKB have participated in the Äspö HRL during 2002. One organisation, BMWA, has decreased its involvement during the year. A Task Force delegate represents each participating organisation and the modelling work is performed by modelling groups. Together these organisations involve in the order of ten modelling groups. The Task Force meets regularly about once to twice a year.

Different experiments at the Äspö HRL are utilised to support the modelling tasks. To date modelling issues and their status are as follow:

Task 1: Long Term Pumping and Tracer Experiments (LPT-2). Completed.

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

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

Task 4: The Tracer Retention and Understanding Experiment (TRUE), 1st stage. Near complete.

Task 5: Coupling between hydrochemistry and hydrogeology. Near complete.

Task 6: Performance Assessment modelling using Site Characterisation data (PASC). On-going.

Objectives

The Äspö Task Force is a forum for the organisations 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 in the project. 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.

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

Results

The Tasks 1–3 are already completed and the main results can be found in previous Äspö HRL Annual Reports /SKB, 2002/. In this report, ongoing activities and results are only presented for Task 4, 5 and 6.

Task 4

Task 4 consists of several modelling exercises divided into different sub-tasks. Four sub-tasks (4A, 4B, 4C and 4D) constituted to a great extent the preparatory steps for the two sub-tasks 4E and 4F. Tasks 4E and 4F comprise predictive modelling of tracer tests performed with a collection of sorbing, slightly sorbing and non-sorbing tracers. Both sub-tasks model radially converging tests in the same geological feature. The TRUE-1 experiment that formed the basis for this modelling task is reported in /Winberg et al, 2000/ and /Cvetkovic et al, 2000/.

In 2001, the modelling work was completed. This was followed by an evaluation process. For example, the evaluation of the modelling done in sub-tasks 4E and 4F is reported in /Elert and Svensson, 2001/. In addition, the overall evaluation of Task 4 with the purpose to address understanding, methodologies, and motivation/expectations from the viewpoint of the participating organisations is near to be complete and reported.

Task 5

Task 5, is an exercise that specifically studies the impact of the tunnel construction on the groundwater system at Äspö. The modelling is performed with the objective to replicate observed groundwater compositions and flow in the tunnel and at a few control points away from the tunnel.

The modelling exercises by the different modelling groups have all been completed. This was followed by reporting from the different modelling teams. Based on the modelling team reports, work was made to compile results and summarise approaches, executions, and conclusions of Task 5 into one summary report /Rhén and Smellie, 2003/. Also, an evaluation of the task was initiated and performed by external reviewers. The outcome of the review is presented in /Bath and Jackson, 2003/.

Task 6

Task 6 was initiated in 2001. The objectives of this task are to:

- Assess simplifications used is performance assessment (PA) models.
- Assess the constraining power of tracer (and flow) experiments for PA models.
- Provide input for site characterisation programmes from a PA perspective (i.e. provide support for site characterisation programme design and execution aimed at delivering needed data for PA).
- Understand the site-specific flow and transport behaviour at different scales using site characterisation models.

Five sub-tasks (6A, 6B, 6C, 6D and 6E) have been defined within Task 6.

In sub-task 6A, it is attempted to model and reproduce selected TRUE-1 tests with a performance assessment model and/or a site characterisation model in order to provide a common reference.

In sub-task 6B, modelling is performed for selected PA cases at the TRUE-1 site with new PA relevant (long-term/base case) boundary conditions and temporal scales to understand the differences between the use of performance assessment models and site characterisation models. Also, the influence of various assumptions made for performance assessment calculations are investigated. In a variant denoted task 6B2, a line source was used instead of a point source for the injection of solutes.

The modelling work is completed for sub-tasks 6A and 6B. During 2002, work on modelling reports of sub-tasks 6A, 6B, and 6B2 have been made by the modelling groups. Results were presented at the 16th Task Force Meeting at Äspö HRL in June 2002.

In sub-task 6C, a 50–100 m block scale synthesised structural model is developed using data from the Prototype Repository, TRUE Block Scale, TRUE-1, and FCC (Fracture Characterisation and Classification). The work to construct the model was near to be complete in 2002. The developed model is to be used as input data to sub-task 6D.

2.8.2 Numerical Modelling of Groundwater Flow (NUMMOD)

Background

Mathematical models for groundwater flow and transport are important tools in the characterisation and assessment of underground waste disposal sites. SKB has during the years developed and tested a number of modelling tools.

Several modelling concepts such as Stochastic Continuum (SC) and Discrete Fracture Network (DFN) concepts have been used to model the Äspö HRL region. The SC approach has been used for the regional and site scale models of the Äspö HRL /Svensson, 1997a,b/, and in the laboratory scale model the starting point was a fracture network for assigning hydraulic properties to a SC model /Svensson, 1999a/.

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

Objectives

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

The specific objectives with the updated models are:

- Test and improve new methodology of generating a conductivity field based on a DFN model in a SC modelling approach.
- Develop models for transport and dispersion.
- Improve the methodology for calibration and conditioning of the model to observed conductive features included in 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 and corresponding properties from the Rock Visualisation System (RVS) to the numerical code for groundwater flow.
- Increase the details in the models based on new knowledge of the Äspö site collected during the last years.

Modelling concept

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

Results

The main tasks for 2002 were:

- Reporting of Part 1 of NUMMOD in two separate reports.
- Launching of versions 1.0 and 2.0 of DarcyTools.
- Execution of Part 2 of NUMMOD.
- Participation in Task 6 of the Äspö Task Force.
- Use of DarcyTools in site characterisation programme (did not start during 2002).

Reporting

The last feasibility study within NUMMOD Part1 was published, *Simulation of transport in a sparsely fractured rock – Modelling of sub-grid effects* (internal report).

The final reporting was done in two separate reports: *Darcy Tools – Concepts, Methods, Equations and Tests* (internal report), and *DarcyTools – Software description and documentation. Version 1.0* (internal report). The first report presents the concepts and methods implemented in DarcyTools. However, it also provides a set of test cases on which DarcyTools has been tested, and summarises Part 1 of NUMMOD, i.e. the feasibility studies performed mainly prior to year 2002. The second report is mainly a description of the numerical code itself.

DarcyTools version 1.0 and 2.0

DarcyTools version 1.0 was launched during 2002 and contains the major code development performed within Part 1 of NUMMOD. The launching of version 2.0 was delayed in order to accommodate needs from the up-coming site investigation programme where DarcyTools is to be used.

NUMMOD Part 2

The second part of NUMMOD will not be performed as planned within the Repository Technology unit. Instead, the development foreseen within NUMMOD Part 2 is now handled within the Safety and Science and Site investigation units. However, some of the development and tests planned for NUMMOD Part 2 were already addressed within NUMMOD Part 1 during 2002. These activities primarily include an external assessment/review of version 1.0, development of user-friendly input/output interfaces, and additional verification and validation studies using version 1.0.

Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task 6

The scope of Task 6 is to model flow and radionuclide transport in a single fracture and in a fracture network (block scale) for typical field scale experimental conditions and for conditions relevant for performance assessment. The objective is to evaluate how models perform when applied on different temporal and spatial scales. DarcyTools version 1.0 was used in Tasks 6A and 6B where transport in a single fracture was analysed.

2.9 PADAMOT

2.9.1 Background

Palaeohydrogeology is a relatively new term used as a common name for information from fracture minerals that is used for interpretations of past hydrogeochemical and hydrogeological systems. The need for such interpretations has become evident in the geological/hydrogeological modelling of sites within the radwaste programmes of several countries and therefore an EC founded 3 year project with the name EQUIP (Evidences from Quaternary Infills for Palaeohydrogeology) was started in 1997. The EQUIP project was concentrated on the formulation of a methodology for how to conduct a palaeohydrogeological study; what minerals to use, what analyses to perform, and also the preferred sequence in which the different analyses should be carried out. Each participating country also carried out analyses within their selected sites. Within the Swedish study the selected site is Äspö and the drill cores used was from the pre-investigation boreholes KAS02, KAS03 and KAS04. Some samples from the 1700 m deep borehole KLX02 from the nearby mainland Laxemar were also included. The study was concentrated on calcite as this mineral relatively quickly responds to changes in groundwater chemistry. However, information from Fe-oxides and sulphides has also been included when possible.

When the EQUIP project ended in 2000 /Bath et al, 2000/ there was a need for continued fracture mineral investigations and model testing of the obtained results and therefore a new EC-project was initiated in the beginning of 2002 running to the end of 2004. This project is called PADAMOT (Palaeohydrogeological Data Analysis and Model Testing).

2.9.2 Objectives

The objectives for the PADAMOT project include:

- Further developments of analytical techniques that exploit the rapid advances in instrumental capabilities especially for quantitative microanalyses for trace elements and isotopes for dating,
- Development of modelling tools to interpret data quantitatively and to relate it to both water-rock reactions at the scale of mineral crystals and also to evolution of the groundwater systems at larger scales
- Focus of further research to investigate specific processes that might link climate and groundwater in low permeability rocks.

The Swedish part of the PADAMOT study will concentrate on the two work packages WP 2 (Palaeohydrogeological characterisation of sites) involving applications of several analytical techniques on fracture filling calcites dominantly from KLX01, and WP 5, which deals with Performance Assessment applications of palaeohydrogeological data and modelling.

2.9.3 Results

The work has continued from the base created in the EQUIP study, with sample preparation and analyses of the samples from drill core KLX01. The KLX01 borehole is situated on the mainland (Laxemar) west of the location for the Äspö HRL. The hydrogeological inflow character is a little bit more pronounced in the area of this borehole than in the area of Äspö. The groundwater end-members are the same as those identified at Äspö i.e. present meteoric water, Baltic Sea water, glacial water, and brine water. However, the Baltic Sea component is relatively small (< 15%) whereas the glacial component is significant in some samples (around 30%) according to M3 modelling carried out within the Task 5 in the Äspö Task Force on Modelling of Groundwater Flow and Solute Transport. In M3 modelling the assumption is that the groundwater chemistry is a result of both mixing and water/rock reactions.

Compared with the calcite samples from fractures in drill cores from the entire Äspö the fracture samples from the KLX01 drill core may reflect a deeper influx of meteoric water and past melt water (that may in the upper part possibly have been oxygenated).

The basic idea behind the sampling/analysis programme is therefore to distinguish and characterise the possible recent low temperature calcites and this is made by using stable isotope analyses, microscopy and trace element analyses. Based on these analyses a number of samples for detailed micro scale studies are select.

Within the project, 44 samples have been chosen ranging in depth from 3 to 1056 m. Bulk analyses of stable carbon and oxygen isotopes in fracture carbonates have been carried out. From the sampled and analysed calcites, approximately 25 samples were selected for trace element analyses using ICP-MS on leachates from the samples in order to avoid in-mixing of silicates. Eighteen samples have been analysed for Strontium isotopes and thin section preparation is ongoing.

In 2–3th of October a workshop was held in Brussels on the theme of Palaeohydrogeology organised by the PADAMOT co-ordinators. In addition to a good discussion about how to optimise palaeohydrogeological investigations the workshop provided possibilities to discuss knowledge exchange, which was acknowledged.

3 Disposal technology

3.1 General

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

It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, are conducted under realistic conditions and at appropriate scale. A number of large-scale field experiments and supporting activities are therefore conducted at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing, and will together form a major experimental 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, backfill, sealing, plugging, monitoring and also canister retrieval.
- To integrate these methods and procedures into a disposal sequence, that can be demonstrated to meet requirements of quality in relation to relevant standards, as well as practicality.

With respect to repository function, the objectives are:

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

The main experiments that are installed or under way are:

- Prototype Repository.
- Backfill and Plug Test.
- Canister Retrieval Test.
- Long Term Test of Buffer Material.
- Low-pH cementitious products.
- KBS-3 method with horizontal emplacement.
- Pillar Stability Experiment.

3.2 Demonstration of repository technology

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

The engineering experiments at Äspö HRL, except for the Prototype Repository, are now implemented and are in the operational phase for data collection. This is valid for the Backfill and Plug Test, Canister Retrieval Test, Long Term Test of Buffer Material. Regarding the Prototype Repository, the inner section with four canisters was installed at the end of 2001. The installation of the canisters, bentonite blocks, and the plug were originally planned during 2002 but due to a malfunction in other heaters of the same design the installations in the outer section were postponed until the cause of the malfunction was identified. According to present plans the canisters and buffer in the outer section will be installed during 2003.

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

3.3 Prototype Repository

3.3.1 Background

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

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

The Prototype Repository is co-funded by the European Commission for a 42 months period starting September 2000 with SKB as co-ordinator.

3.3.2 Objectives

The main objectives of 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 during a long time, possible up to 20 years. This is made to provide long-term experience on repository performance to be used in the evaluation that will be made after the initial operational stage in the real deep repository.

3.3.3 Experimental concept

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

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

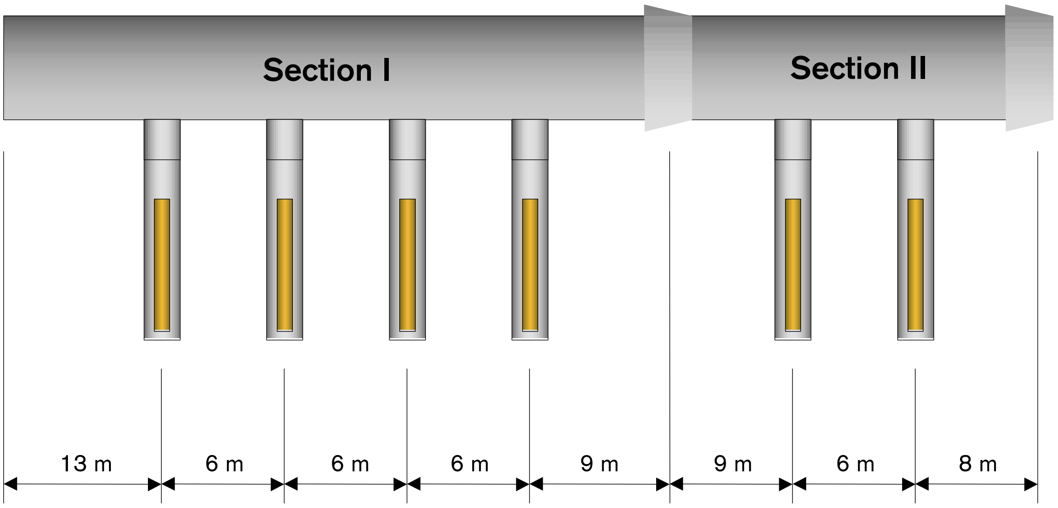


Figure 3-1. Schematic view of the layout of the Prototype Repository. (not to scale)

Decision as to when to stop and decommission the test will be influenced by several factors, including performance of monitoring instrumentation, results successively gained, and also the overall progress of the deep repository project. It is envisaged that the outer test section will be decommissioned after approximately five years to obtain interim data on buffer and backfill performance. Instrumentation will be used to monitor processes and properties in the canister, buffer material, backfill and the near-field rock.

3.3.4 Results

Delay due to malfunction of heater's electrical system

The original plan was to continue the installation of the outer section after Christmas 2001 and cast the plug in the autumn time. But, the heaters in the Canister Retrieval Test had exhibited a decrease in the electrical insulation to earth late 2001, and the construction of these heaters were the same as the heaters in the Prototype Repository, so it was deemed needed to understand the cause of the malfunction before the canisters in the outer section were installed.

The investigations started at once but lasted a bit into the autumn of 2002 before a clear opinion of the cause of the malfunction could be verified. It became evident that pyrolysis of the insulation material around cables to the heaters and water in the magnesium oxide in the heater elements caused an electrolytic mist. The mist decreases the electrical isolation toward the earth in the cold part at the top of the canister with insulation-free cables attached to the lead-through Gisma plugs. Another weak point was the lead-throughs in the lid themselves, which contain tephlone and epoxy, the latter material known to decrease its electrical insulation properties with increased temperature. Based on these findings a new design of the lead-throughs was developed and constructed.

A decrease in the insulation in the 4 installed canisters/heaters was observed, but it was not as drastic as in the Canister Retrieval Test. No specific action was deemed necessary to be taken in order to improve the operating conditions for the 4 installed canisters.

Measurements during operation

A number of sensors are installed in the buffer, backfill and surrounding rock, and a general conclusion after about 1.5 years of operation is that the measuring system and transducers work well. 40 out of 253 sensors (not counting the 64 water pressure sensors in the rock, which are working) are out of order, the majority (29 pieces) being relative humidity sensors which fail at water saturation.

The power in the 4 installed canisters have been kept at a constant 1800 W per canister from start (September 17th, 2001 for hole 1, September 24th, 2001 for hole 2, October 11th, 2001 for hole 3, and October 22nd , 2001 for hole 4). On September 17th, 2002 was the power decreased to 1780 W in all canisters in order to simulate the natural decay that will take place in the real canisters with spent fuel. The instruments installed in the inner section are given in Table 3-1.

Table 3-1. Instruments installed in the inner section – Section I – of the Prototype Repository.

Measurement	Canister	Buffer in deposition holes 1 and 3	Backfill	Rock
Temperature *	Every m along fibre optic cables	32	20	37
Total pressure		27	18	
Pore water pressure		14		23
Water pressure		64		
Relative humidity		37	45	
Geoelectric chain		1		
Displacement		6 (dep. hole 3)	4 (top of buffer)	

* Temperature is also measured by all relative humidity sensors.

Buffer and backfill

The data readings show a marked wetting of the buffer in the innermost deposition hole (see Figure 3-2) and a slow wetting in the other three holes. The wetting of the backfill is fastest over deposition hole 3. The maximum temperature of the canisters differs substantially. It has risen to about 77°C on the surface of the canister in deposition hole 1, to about 99°C in deposition holes 2 and 3, and to about 91°C in deposition hole 4, see Figure 3-3. It is notable that the temperature in the rock around deposition hole 1 is 7°C lower than around the other holes. One reason is judged to be the influence of neighbouring canisters. The absolute difference is, however, not scientifically verified, as the measurement on the surface of the canisters is made by optical fibres, which have not been finally calibrated in place yet, while the temperature in the bentonite blocks is measured with thermocouples, which were calibrated before installation.

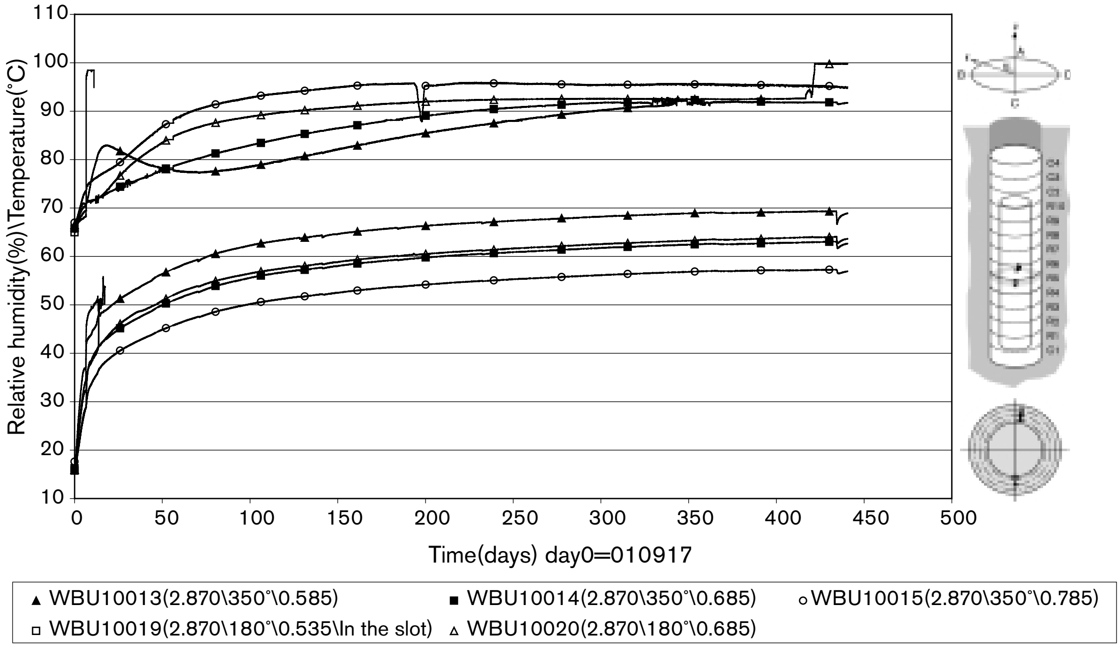


Figure 3-2. Relative humidity in the central bentonite block in deposition hole 1. Temperature values are those measured by the relative humidity sensors.

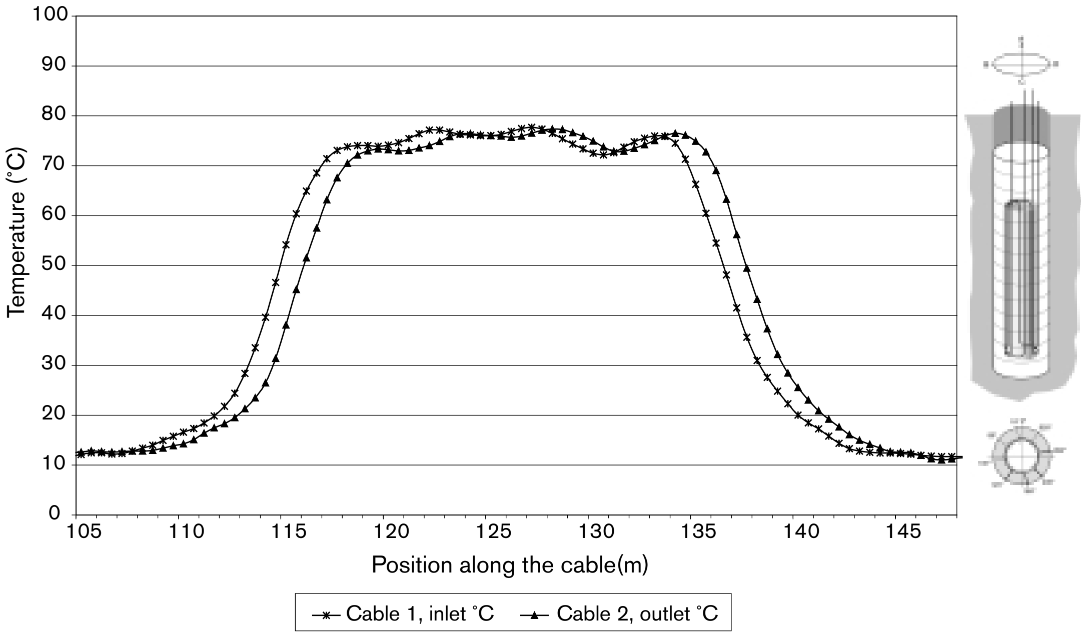


Figure 3-3. Temperature on the surface of the canister in deposition hole 1.

Geoelectric monitoring is made in the backfill between deposition hole 2 and 3 for registration of the development of its saturation. A clear tendency of increased saturation is observed with a water content of 16–17% close to the rock wall (compared to 13–14% after installation).

Canister displacement

Measurements to register canister displacement are made in deposition hole 3. Six displacement sensors are grouped into one measuring section, placed at the bottom of the canister. Three sensors are vertically placed and three are horizontally placed. The data collected since June 23^{rd}, 2001 show a clear and continuous sink of the canister after an initial heave. The maximum sink and heave observed so far are less than 2 mm respectively.

Water pressure in the rock

A large number of boreholes have been instrumented with one or several packers, where the water pressure in the surrounding rock will be measured. In general the result from the inner section is that packed-off sections of the borehole close to the rock wall have lower pressure than sections away from the Prototype Repository tunnel. In most cases the measured head has an increasing trend, although several sections have a slightly decreasing trend since the summer of 2002.

Conceptual modelling and model development

The evolution of the buffer and backfill is being tested and modelled with respect to temperature (T), water migration (H), stress and strain (M), as well as to chemistry (C) and biology (B). Five THM models have been proposed to be used by the individual teams engaged in the study and some of them also include possibilities to add chemical processes in the buffer evolution. One model deals solely with water chemistry.

The work is performed under the following sub-packages:

- Water and gas sampling and analysis.
- Hydraulic tests in rock.
- THM laboratory tests on buffer and backfill properties.
- Laboratory tests on mechanical properties of rock.
- Laboratory determination of cracks in EDZ.
- T and TM modelling of rock.
- HM and THM modelling of rock.
- THM modelling of buffer, backfill and interaction with near-field rock.
- C modelling of buffer, backfill and groundwater.

Hydraulic tests in the rock

A continuum model based on a fracture network has been developed and modelling work performed, which has been published /Svensson, 2001/. A Discrete Fracture Network model has also been worked out and published /Stigsson et al, 2002/. Focus has been on the hydraulic performance and groundwater salinity of the Äspö rock mass and particularly on the pressure and flow conditions in the near-field:

- Two Discrete Fracture Network versions were worked out, that both exaggerate the water inflow into the deposition holes. Improvements are planned.
- Simple analytical predictions of the mean inflow rate into the deposition holes gave values ranging from ten times to one tenth of the measured flow rates.
- A study has been made for modelling the groundwater pressure and salinity distributions around the Prototype Repository area. It is based on a fracture network with given transmissivity distribution that is converted to a conductivity field in a continuum model with a cell size of 1 m close to the tunnel. The boundary conditions were generated by use of larger scale models. Variable density flow is included in the modelling. Two main cases were modelled: (a) present situation with open deposition holes, (b) inner and outer sections with canisters and buffer in the deposition holes and backfilled tunnels.

Direct measurements indicate that the average bulk hydraulic conductivity (K) of the near-field rock around the deposition holes is 10^{-12} to $4 \cdot 10^{-10}$ m/s. Using rock structure data a deposition hole should be intersected by about 3 steep and 4 flat lying, significantly water-bearing fractures, which somewhat overrates the actual numbers. The average inflow of water in the holes is less than 0.006 l/min in all the holes except deposition hole 1, which has 0.08 l/min.

The water pressure at about 2 m distance from the tunnel wall is between 100 kPa and 1.5 MPa. Varying the hydraulic conductivity of the backfill in the modelling from 10^{-11} to 10^{-9} m/s gave corresponding water pressure distributions in the rock.

In situ measurement of the Excavation Disturbed Zone (EDZ) has been made in the access tunnel immediately in front of the Prototype Repository test site. Five shallow boreholes were drilled perpendicularly to the tunnel wall and flow measurements made for determining the hydraulic conductivity. The outcome of the tests showed that the hydraulic conductivity within about 10 cm distances from the tunnel wall is higher than in the rock matrix further out from the wall. Within 1 cm distance the conductivity was found to be about 10^{-10} m/s, while it was estimated to be 10^{-12} to 10^{-10} m/s at a distance of 1 to 10 cm.

THM laboratory tests on buffer and backfill properties

Laboratory experiments were conducted with mixtures containing sodium (MX-80) or calcium-bentonite (Calcigel) and water from Äspö. Multiple hydraulic conductivity column experiments were performed at 20°C for the bentonite/crushed rock mixtures. The corresponding values for a temperature of 90°C were then estimated using the experimentally determined correction factors to account for the temperature dependence of viscosity and density. The mean hydraulic conductivity for MX-80/crushed rock mixtures rises from $1.64 \cdot 10^{-11}$ m/s at 20°C to $4.87 \cdot 10^{-11}$ m/s at 90°C for the assumed backfill density. Calcigel/crushed rock mixtures showed a mean hydraulic conductivity at 20°C of $4.93 \cdot 10^{-9}$ m/s and $1.46 \cdot 10^{-8}$ m/s at 90°C. The thermal laboratory experiments were analysed using inverse modelling techniques. The iTOUGH2 *inverse modelling* code was used in combination with the EOS7 module of TOUGH2 to simulate the experiment and to estimate the thermal conductivity and heat capacity of the bentonite/crushed rock mixture by matching the observed temperatures at discrete points in space and time. The simulated temperature distribution fitted the measured data very well at all locations along the column and for all times. The inversely estimated thermal conductivity ranged from 1.6 to 2.2 W/m, K, and the specific heat from 810 to 1020 J/kg, K. However, the evaluation of the effective parameters was very sensitive to heat loss through the insulation. The newly developed experimental setup in combination with inverse modelling made it possible to identify the key parameters governing the hydraulic and thermal processes of bentonite/crushed rock mixtures under repository conditions.

The main results can be summarised as:

- Backfill of Na-bentonite with the intended density and percolated with Äspö water gave an ultimate conductivity of $7.4 \cdot 10^{-12}$ m/s.
- The threshold capillary pressure for the Na-bentonite backfill saturated with Äspö water is approximately 0.99 MPa at 20°C and 0.83 MPa at 90°C.
- Addition of Äspö water to MX-80 backfill is calculated to release 20% of the adsorbed Na and 49% of the Ca.
- Application of the code TOUGH2 V2.0 Code, Module EOS7 (water, air, saline water, non-isothermal conditions) indicates that there is only a minor influence of the ion content and osmotic potential on the thermo-hydraulic processes. With a pressure gradient of 2 MPa over 0.3 m clay with an initial degree of water saturation of 49%, the resulting saturation zone is 7 cm after 100 days.

Laboratory determination of cracks caused by boring machine (EDZ)

Work has been made on the porosity and conductivity of the excavation disturbed zone (EDZ) of the access tunnel to the Prototype Repository test sits. Micro-fracturing and porosity in the excavation damage zone have been studied by using the 14C-polymethylmethacrylate (14C-PMMA) method and scanning electron microscopy (SEM). A total of 12 samples from the deposition holes 3 and 4 (diorite) were taken. The porosity of the damaged rock zone is clearly higher than the porosity of undisturbed rock. The thickness of the fractured zone with significantly higher porosity is a few millimetres and the average depth of the damaged zone ranges from 10 to 20 mm. Examples of porosity profiles of the samples from deposition holes 3 and 4 are shown in Figure 3-4 and an example of porosity image is given in Figure 3-5. The study reconfirmed the conductivity measurements described under "Hydraulic tests in rock".

THMC Modelling

Examples of modelling work performed by the international participants in the Äspö co-operation are presented in Chapter 5.

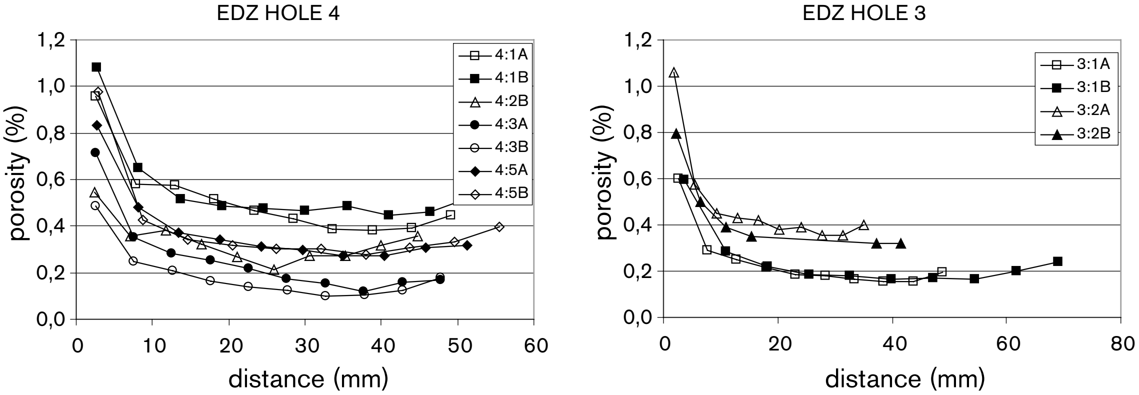


Figure 3-4. Porosity of rock with respect to the distance from the surface of the deposition holes 3 and 4.

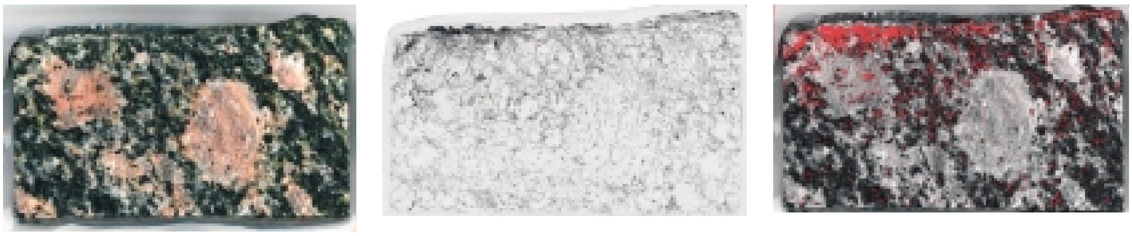


Figure 3-5. Photo image (left), autoradiograph (middle) and superposition image (right) of sample from deposition hole 3. The superposition image has been produced by superimposing the autoradiograph on the photo image and by colouring the regions of high porosity to be red.

3.4 Backfill and Plug Test

3.4.1 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 and casting of the final part of the plug was finished in autumn 1999. The water saturation, with water filling of permeable mats, started in late 1999. In the years up to 2001 the water saturation has continued and data from transducers have been collected and reported. The plug has been grouted and tested and the water pressure in the permeable mats has been increased to 500 kPa in order to shorten the time to reach full saturation.

3.4.2 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.
- Test the function of the backfill and its interaction with the surrounding rock in full scale in a tunnel excavated by blasting.
- Develop techniques for building tunnel plugs and test the function.

3.4.3 Experimental concept

Figure 3-6 shows an axial section of the test layout. The test region, which is about 30 m long and located in the old part of the ZEDEX drift, can be divided into the following three test parts:

- The *inner part* filled with backfill containing 30% bentonite (sections A1–A5 and B1).
- The *outer part* filled with backfill without bentonite and bentonite blocks at the roof (sections B2–B5).
- 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. Figure 3-7 shows a 3D visualisation of the experimental set-up.

The inner test part is 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 is 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.

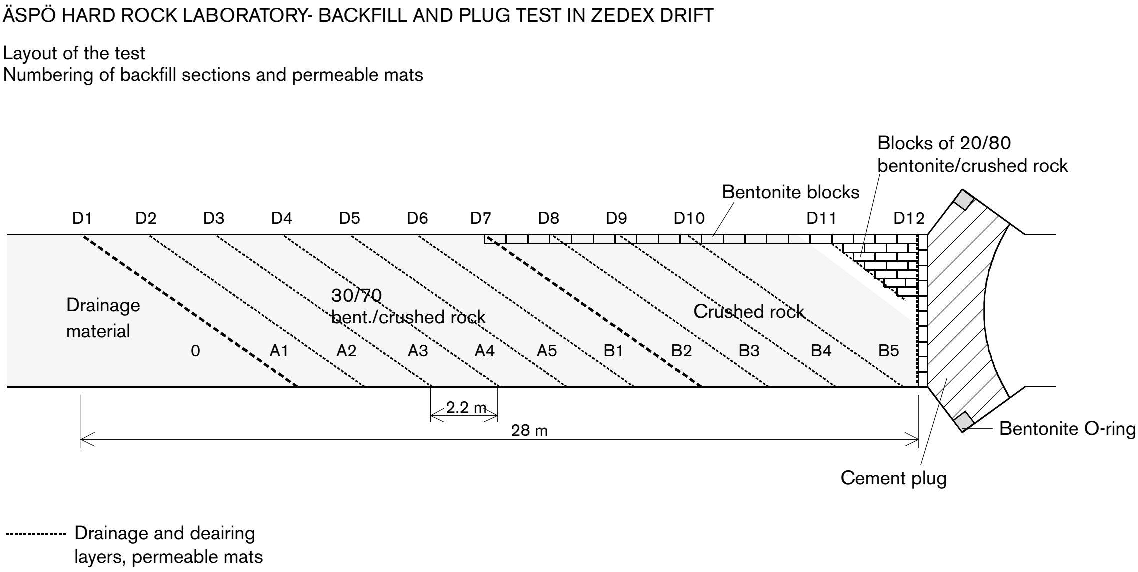


Figure 3-6. An overview of the Backfill and Plug Test.

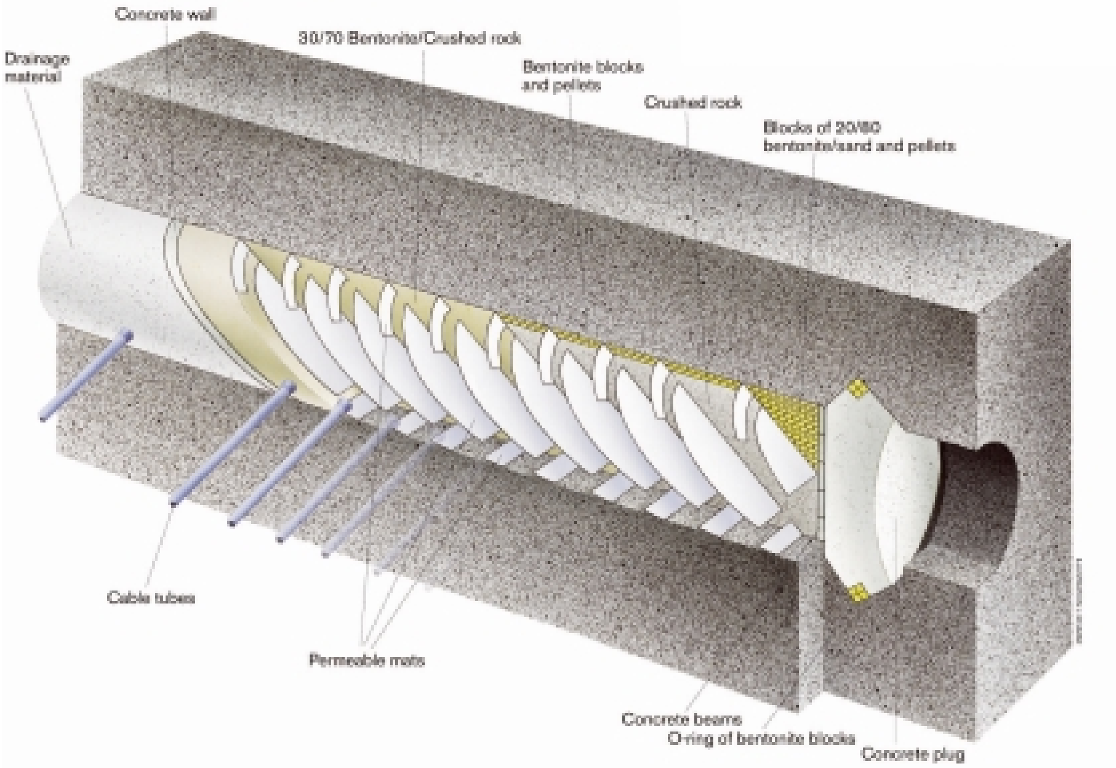


Figure 3-7. Illustration of the experimental set-up of the Backfill and Plug Test.

Each one of the two test parts are about 14 m 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 near-field rock. The mats are also used for the water saturation of the backfill. The mats were installed in both test 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.

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 *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 backfill and rock are 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 are enclosed in Tecalan tubes in order to prevent leakage through the cables. The cables are led through the rock to the data collection room in boreholes drilled between the test tunnel and the neighbouring Demo-tunnel.

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

3.4.4 Results

The final step of increasing the water pressure in the permeable mats from 400 to 500 kPa was taken on January 21. The water pressure has since then been kept constant at 500 kPa.

The amount of water passing through the plug and the surrounding rock has been measured by collecting the water outside the plug. Figure 3-8 shows the results with a direct response of each pressure increase and then a successive reduction in flow until steady state is reached. The results show that the leakage has been rather constant at 0.05 l/min during a long time but has during the last 4 months been reduced from 0.05 to 0.03 l/min.

The test site is situated between the "Demonstration tunnel" and the "TBM tunnel". In order to try to understand the hydraulic effect of the change in water pressure inside the test tunnel on the surrounding rock dams for measuring the water flow into the "Demonstration tunnel" and the "TBM tunnel" have been built.

Water saturation, water pressure and swelling pressure in the backfill, and water pressure in the surrounding rock have been continuously measured and recorded. Two data reports covering the period up to 2002-07-01 /Goudarzi et al, 2002a/ and the period up to 2003-01-01 /Goudarzi et al, 2003a/ have been released. Figure 3-9 and Figure 3-10 show example of measured results. Figure 3-9 shows the water pressure in the rock measured in the short boreholes about 30 cm below the floor of the tunnel. The strong increase at the end of the diagram is the result of the water pressure increase. Figure 3-10 shows the suction (negative pore water pressure) measured in the centre of some layers of the 30/70 mixture of bentonite and crushed rock backfill at different distances from the mats. The backfill is water saturated at suction about 1000 kPa. The influence of the increase in water pressure is obvious, with a resulting much faster decrease in suction. Today the entire backfill seems to be almost completely water saturated.

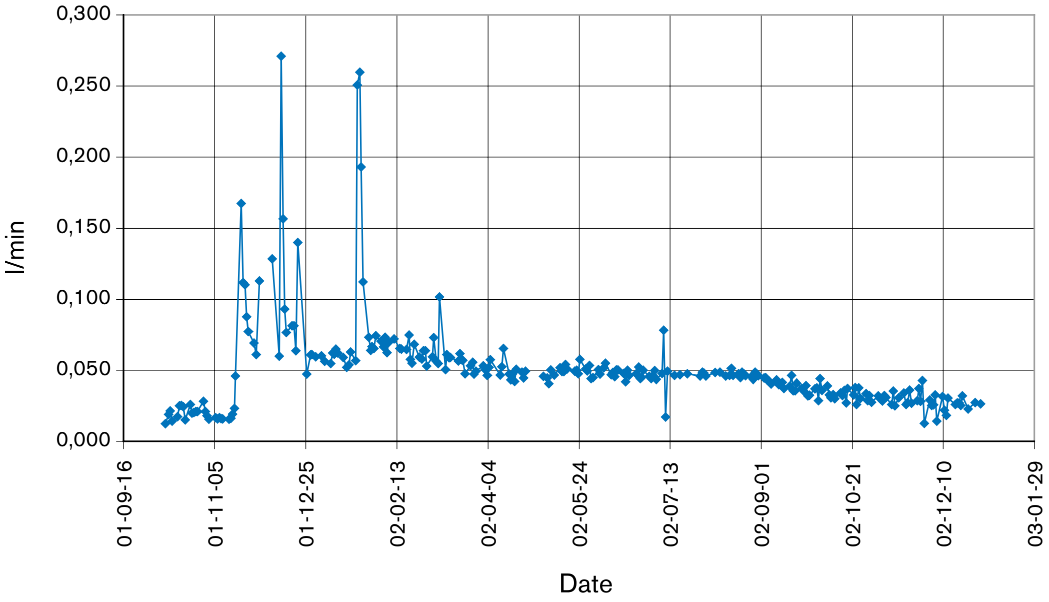


Figure 3-8. *Water flow through the plug and its surroundings. The last very high peak corresponds to the pressure increase from 400 to 500 kPa.*

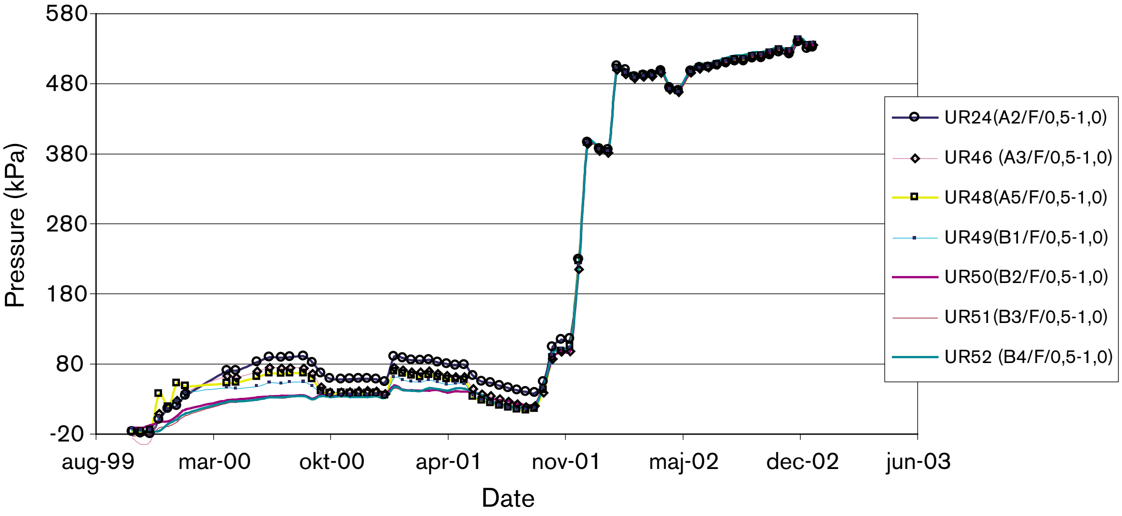


Figure 3-9. *Water pressure measured in the floor 30 cm below the rock surface. UR24, 46, 48, and 49 are placed in the 30/70 sections and the rest in the 0/100 sections.*

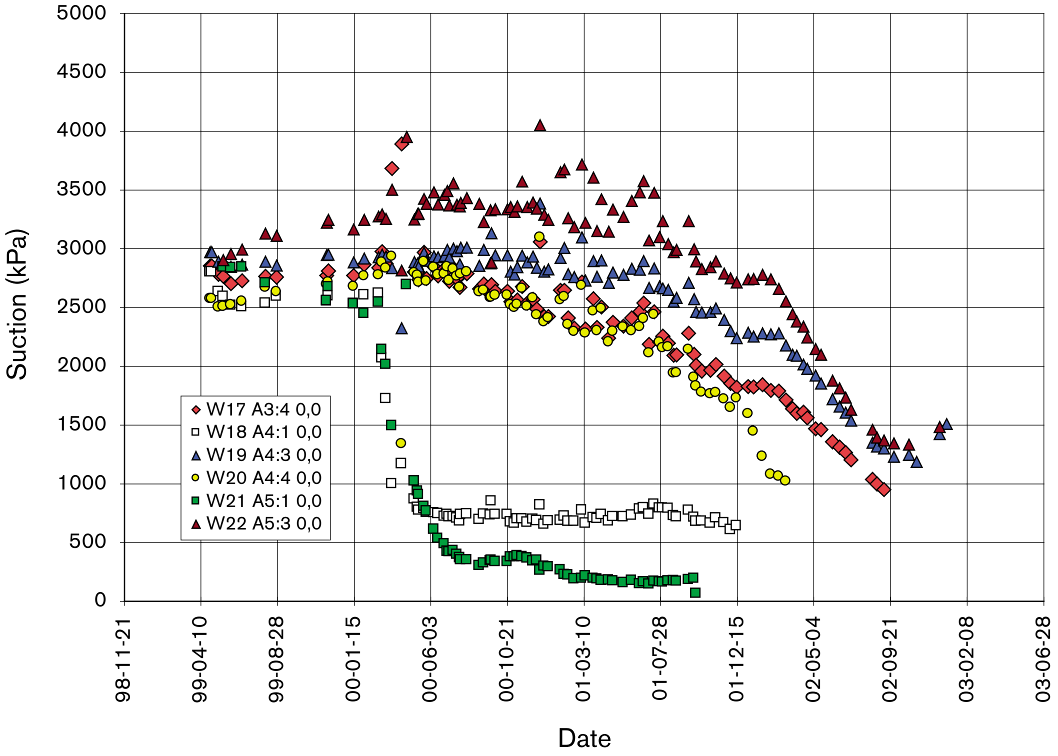


Figure 3-10. *Suction measured in the centre of different layers in the 30/70 backfill. W18 and W21 are placed in the first layer about 20 cm from the mats. W17 and W20 are placed 40 cm and W19 and W22 are placed 60 cm from the mats.*

3.5 Canister Retrieval Test

3.5.1 Background

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

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

3.5.2 Objectives

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

- Two vertically bored test holes in full repository scale, which fulfil the quality requirements deemed necessary for the real repository.
- Careful and documented characterisation of the properties of these holes including the boring disturbed zone.
- Emplacement of bentonite blocks, bentonite pellets and canisters with heaters, and artificial addition of water. However, for different reasons only one of these deposition holes has been used for implementation of the Canister Retrieval Test.
- Saturation and swelling of the buffer under controlled conditions, which are monitored.
- Preparations for testing of canister retrieval.

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

3.5.3 Experimental concept

The Canister Retrieval Test is located in the main test area at the 420 m level. The tunnel is excavated by conventional drill and blast techniques and is 6 m wide and 6 m high. The test is separated into three stages:

Stage I	Boring of deposition hole and installation of instrumented bentonite blocks and canisters with heaters. This hole is covered in the top with a lid of concrete and steel.
Stage II	Saturation of the bentonite and evolution of the thermal regime with measurement of thermal, hydraulic and mechanical processes.
Stage III	Test of freeing the canister from the bentonite, docking the gripping device to the canister lid and lifting of the canister up to the tunnel floor and into the radiation shield on the deposition machine (reversed deposition sequence).

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with a full diameter of 1.65 m and a nominal height of 0.5 m. Instruments for measuring temperature, relative humidity, total pressure and pore pressure were installed in the bentonite in many of the blocks. 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 in the rock and strain gauges in the rock were connected, and additional blocks were emplaced until the hole was filled up to 1 m from the tunnel floor. On top the hole was sealed with a plug made of concrete and a steel plate as cover. The plug was secured against heave caused by the swelling clay with 9 cables anchored to the rock. The tunnel will be left open for access and inspections of the plug support. The experimental set-up is shown in Figure 3-11.

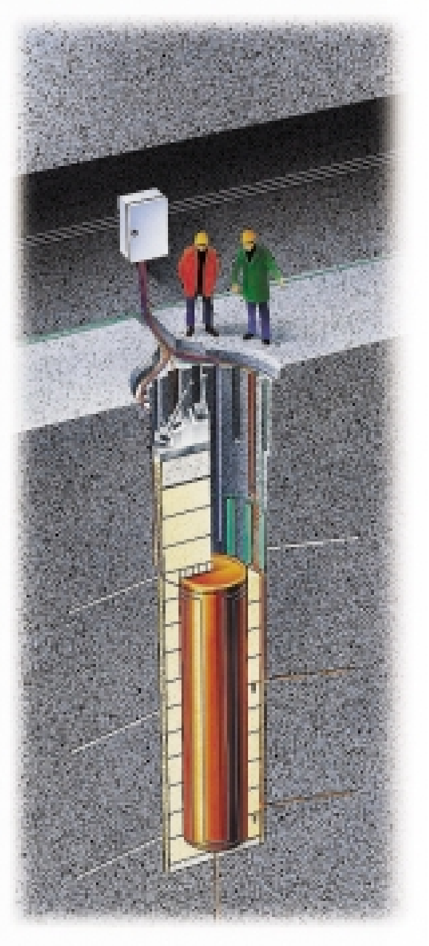


__Figure 3-11.__ Illustration of the experimental set-up of the Canister Retrieval Test.

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

Predicted saturation time for the test is 2–3 years in the 350 mm thick buffer along the canister and 5–10 years in the buffer below and above the canister. Decision on when to start the retrieval tests is dependent on the degree of saturation in the buffer. The instrumentation in the buffer is similar to the instrumentation in the Prototype Repository and yield comparable information during the saturation period. The intention to minimise disturbances during retrieval tests, however, restricts the number and locations of instruments.

3.5.4 Results

The Canister Retrieval Test was installed during year 2000 and the heaters were turned on in October 26 at a constant effect of 1700 W. The effect was increased to the final thermal load, 2600 W, when the temperature had reached approximately 65 degrees on the canister surface on February 13, 2001.

At the end of 2001 two of the 36 electrical heaters failed due to short circuit to earth and no power was generated during one day between November 5 and 6. The heaters were also shut off during one week between March 4 and 11 2002 for control measurements. The remaining heaters have worked well during 2002, in the respect that no more failures have occurred. The power in the heaters were reduced from 2600 W to 2100 W on September 9, 2002 in order to lower the temperature in the canister and in this way increase the resistance to earth in the heater elements.

The mats for artificial wetting were flushed and the water pressure was increased from 50 to 850 kPa at two occasions, in September and October 2002.

Measurements

A large number of parameters are measured during the test to provide a basis for modelling purposes. Two data reports covering the period up to 2002-05-01 /Goudarzi et al, 2002b/ and the period up to 2002-11-01 /Goudarzi et al, 2003b/ have been released. Table 3-2 shows the parameters that are measured. Selected characteristic values from 2000-10-26 until 2002-12-30 are shown in Figure 3-12 to Figure 3-15. Figure 3-12 and Figure 3-13 show the temperature and the total pressure in the buffer and rock along one line at mid-height heater. Figure 3-14 shows the relative humidity in the buffer along one line on top of the heater and Figure 3-15 shows the anchor forces.

The relative humidity sensors indicate that the bentonite between the rock and the canister is close to water saturation although the wetting seems to be somewhat uneven and the total pressure has not reached the expected values yet. Entrapped air and clogging of the filters may explain the inhomogeneous appearance. The filters are now flushed regularly in order to avoid such effects.

Table 3-2. Measurements in Canister Retrieval Test.

Type of measurement	Number of sensors	Comments
Temperature inside canister	18	
Temperature on canister surface	4 loops of optic cables	
Temperature in the buffer	32 (+ in many other sensors)	Figure 3-12
Temperature in the rock	40	Figure 3-12
Rock stress + strain	8 + 9	
Total pressure in buffer	27	Figure 3-13
Pore pressure in buffer	14	
Relative humidity in buffer pores	55	Figure 3-14
Heater effect	1	
Artificial watering volume	1	
Artificial watering pressure	1	
Vertical displacement of plug (mm)	3	
Forces in rock anchors (kN)	3	Figure 3-15

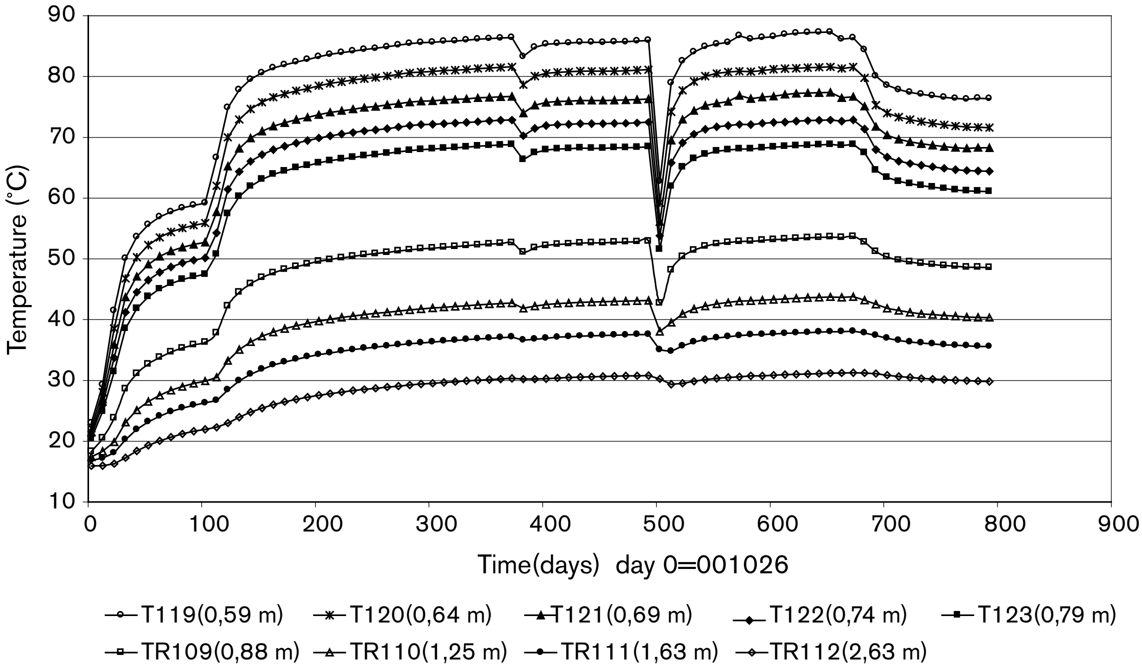


Figure 3-12. *Temperature in the buffer and rock as a function of the time from start. The sensors are located at mid height canister along the same radial line, with the distance from the canister centre line noted in the table of signs (canister surface at 0.53 m; rock surface at 0.88 m).*

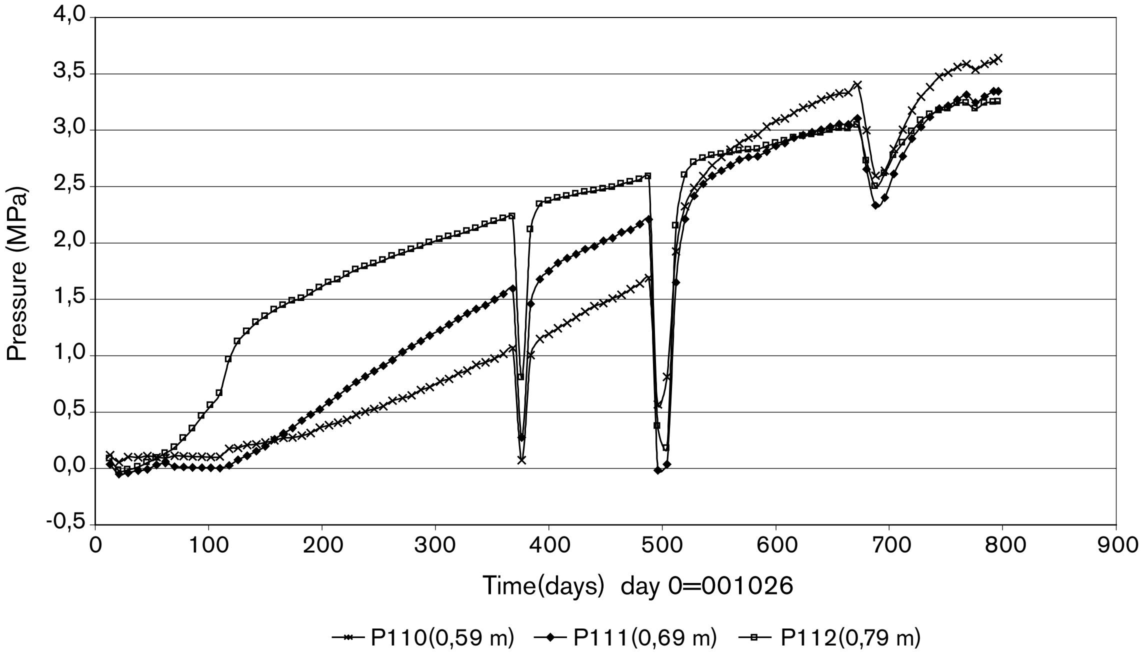


Figure 3-13. *Total pressure in buffer as a function of the time from start. The sensors are located mid height canister along the same radial line, with the distance from the canister centre line noted in the table of signs (canister surface at 0.53 m; rock surface at 0.88 m). The first two dips are caused by heat shut down and the third dip is caused by the power decrease.*

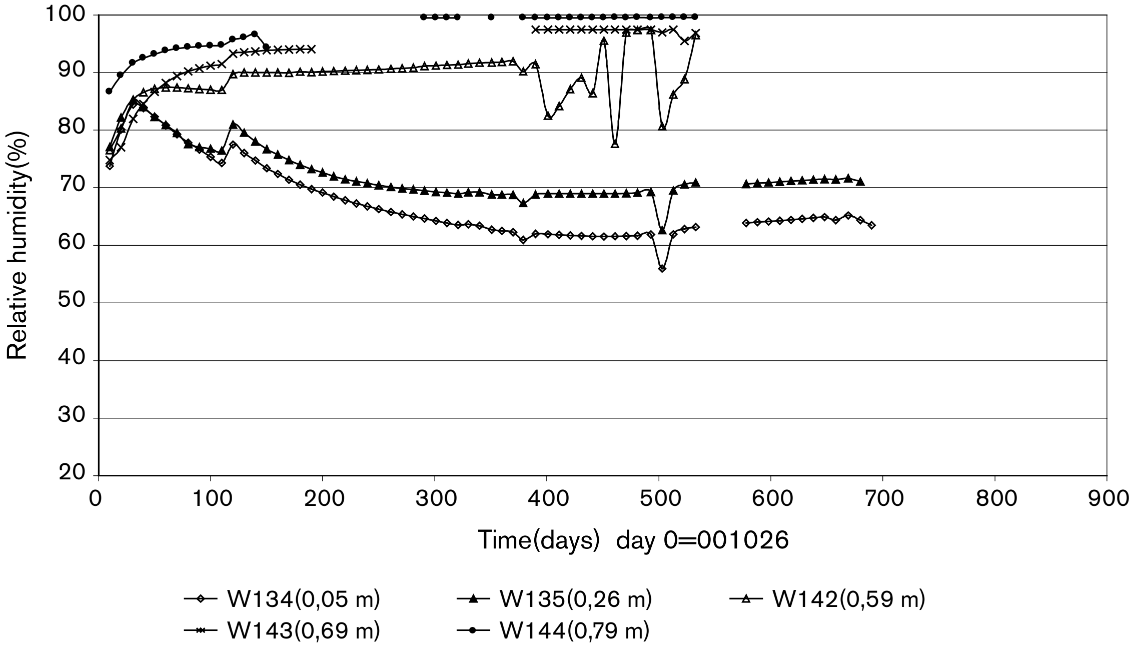


Figure 3-14. *Relative humidity in buffer as a function of the time from start. The sensors are located at the top of the canister along the same radial line, with the distance from the canister centre line noted in the table of signs (canister surface at 0.53 m; rock surface at 0.88 m).*

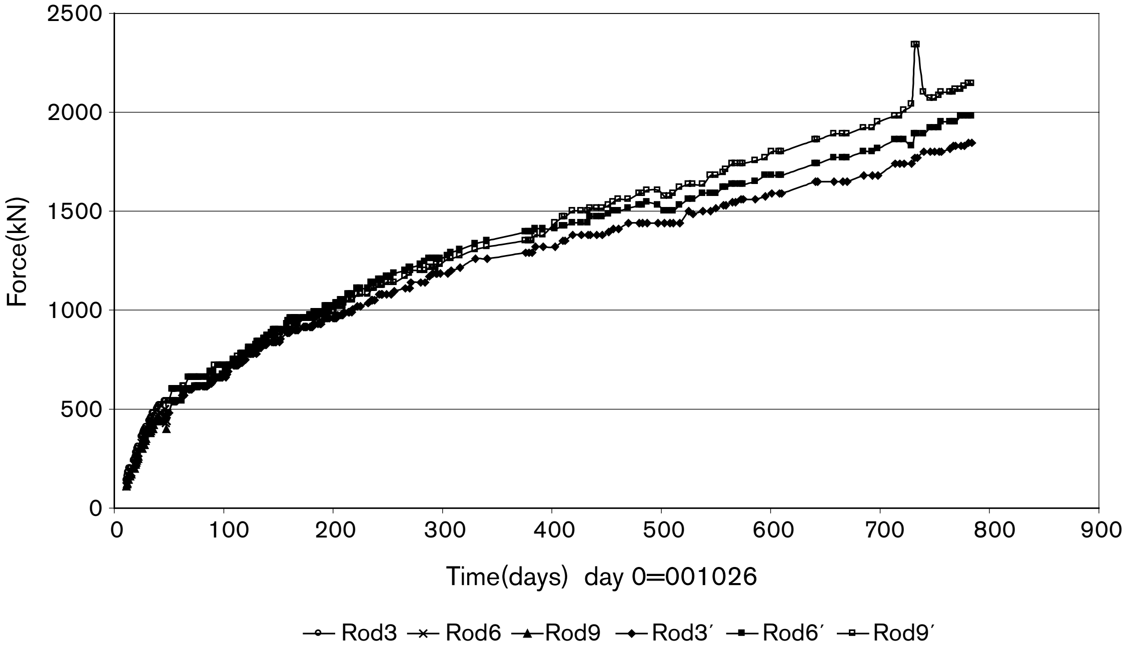


Figure 3-15. *Tensile forces in rock anchors for the retaining plug as a function of the time from start. After about 40 days the force is multiplied with 3 in order to illustrate the total force (only 3 out of 9 anchors were measured after 40 days).*

3.6 Long Term Test of Buffer Material

3.6.1 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 minimise water flow over the deposition holes.

The decaying power from the spent fuel in the HLW canisters will give rise to a thermal gradient over the bentonite buffer by which original water will be redistributed parallel to an uptake of water from the surrounding rock. A number of laboratory test series, made by different research groups, have resulted in various buffer 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.

3.6.2 Objectives

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

- Data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, cation exchange capacity and hydraulic conductivity.
- Check of existing models on buffer-degrading processes, e.g. illitization and salt enrichment.
- Information concerning survival, activity and migration of bacteria in the buffer.
- Check of data concerning copper corrosion, and information regarding type of corrosion.
- Data concerning gas penetration pressure and gas transport capacity.
- Information which may facilitate the realisation of the full scale test series with respect to clay preparation, instrumentation, data handling and evaluation.

3.6.3 Experimental concept

The test series, given in Table 3-3, concern realistic repository conditions except for the scale and the controlled adverse conditions in four tests (A series). The testing principle for all tests is to emplace "parcels" containing heater, central tube, pre-compacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m, see Figure 3-16.

Adverse conditions in this context refer to high temperatures, high temperature gradients over the buffer, and additional accessory minerals leading to i.e. 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 heaters' 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 tests are performed.

Table 3-3. Long-term test series.

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

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

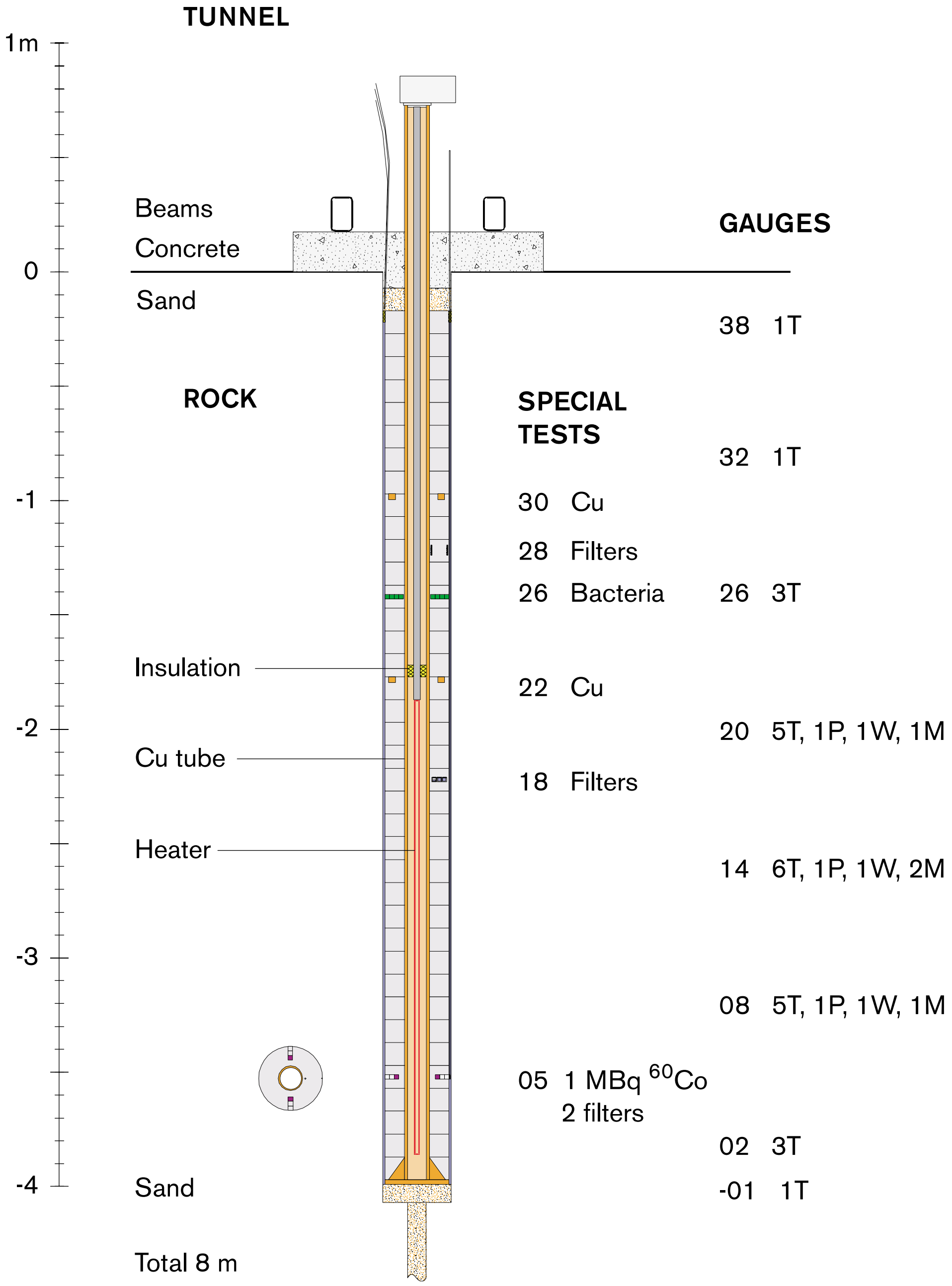


Figure 3-16. *Cross-section view of an S-type parcel. The first figures in column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.*

3.6.4 Results

The analysing work with material from parcel A0 are almost completed, and compilation of results are presently being reported. The analyses of clay chemistry and mineralogy show minor redistribution of accessory minerals. Precipitation of gypsum in the warmer parts of the parcel was the most pronounced mineralogical change (Figure 3-17). This effect is attributed to the decreasing solubility with increasing temperature. Possible changes in montmorillonite structure were analysed by various cation exchange capacity and XRD (X-ray diffraction) techniques, and no significant changes were found. Minor uptake of copper from the central tube and from copper containing instrument tubing was found. The maximum copper content was as low as 0.1% of the total clay mass, which corresponds to around 5% of the cation exchange capacity of the clay. A tendency of change in magnesium distribution was noticed.

A large number of tests and analyses concerning physical properties have been made. The results show that the parcel clay buffer was not fully water saturated, and a gradient from rock to the warmest parts was found for water ratio and density. Swelling pressure and hydraulic conductivity measurements show no sign of deterioration of the sealing properties (Figure 3-18).

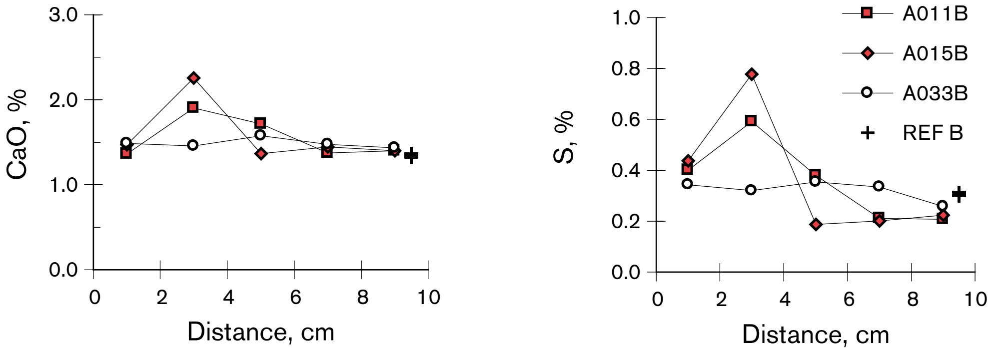


Figure 3-17. *Calcium and sulphur content from ICP/AES (Inductively Coupled Atomic Emission Spectroscopy) analyses of bulk clay material. The x-axis represents distance from the central copper tube. Filled markers represent hot positions in the clay and non-filled represents cold positions high up in the parcel. Crosses show reference values.*

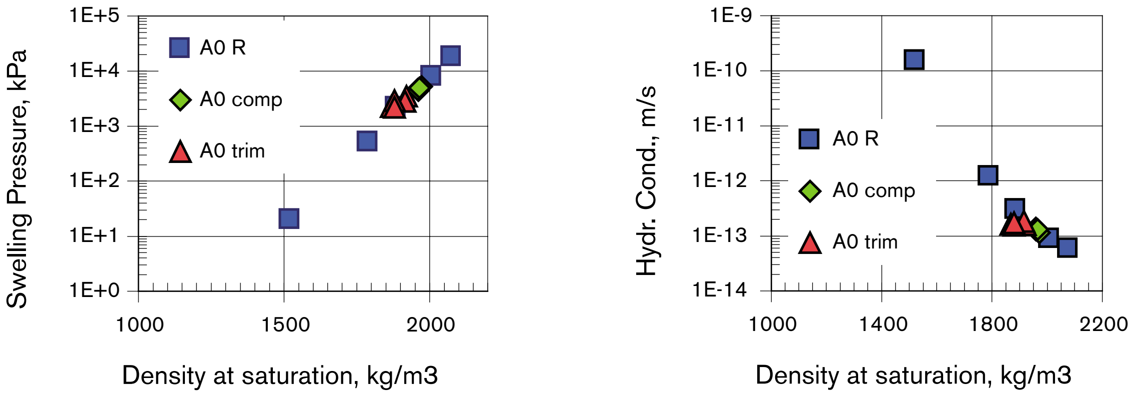


Figure 3-18. *Swelling pressure and hydraulic conductivity results from reference material (squares), rewetted parcel material (diamonds), and trimmed parcel material (triangles).*

The distributions of radioactive tracers (^{57}Co and ^{134}Cs) were measured at the Nuclear Chemistry department at KTH, Stockholm, and the results are in accordance with previous laboratory and CHEMLAB field-test results.

The clay and pore water analyses made at Reactor department at VTT, Helsinki, shows minor cation exchange reactions, minor redistribution of original ions and pH changes in the range of 7 to 9.

The analysis results from the A0 parcel have been used by Enviros, Barcelona to model the chemical and mineralogical evolution in the buffer. The modelling was made by use of a transport code coupled with a geochemical code (PHAST) and the aim was to improve the results compared to previous modelling by taking the prevailing temperature gradient into account.

Corrosion of embedded copper coupons was analysed, by Rosborg Consulting/Studsvik Material in Nyköping, and an average corrosion rate of less than 4 µm per year was shown, which is the same value as was found for the previous S1 parcel. The nature of the corrosion can be classified as general but somewhat uneven on the micro-scale. No obvious signs of pitting can be claimed.

The remaining ongoing four long-term test parcels have functioned well, and temperature, total pressure, water pressure, and water content have been continuously measured and registered every hour. The bentonite swelling pressure is still increasing in all parcels, although the tests have been running for more than 3 years, showing that water uptake is still ongoing (Figure 3-19).

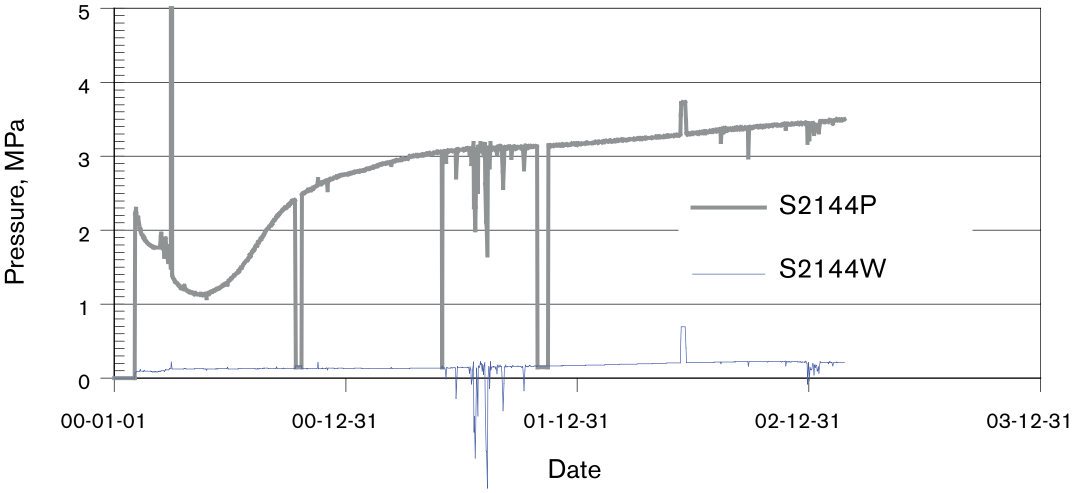


Figure 3-19. *Measured total pressure (upper curve) and water pressure in warmest part of parcel S2 from test start. No water pressure build-up is expected before full swelling pressure is reached.*

3.7 Pillar Stability Experiment

3.7.1 Background

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

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

3.7.2 Objectives

The Äspö Pillar Stability Experiment is a rock mechanics experiment that can be summarised in the following three main objectives:

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

3.7.3 Experimental concept

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

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

Thermocouples, convergence measurements in the open hole, and acoustic emission will be used to monitor the experiment.

3.7.4 Results

A feasibility study has been performed in which the general design of the new tunnel and the experimental area have been defined.

There different sites for the experiment have been studied at the 450 m level. The sites have been evaluated from a practical point of view and with quite extensive geological and hydrogeological characterisations in four new core boreholes. The different sites are shown in Figure 3-20 and the preferred site for the experiment is Alternative 3.

Numerical predictive modelling has been performed with the following codes:

- Examine3D, for 3D stress modelling.
- FLAC^{3D}, for coupled 3D thermomechanical-modelling.
- FRACOD, for 2D fracture stability modelling.
- JobFem, for coupled 2D thermomechanical-modelling.

The modelling results are preliminary since not site specific but average rock mechanical parameters have been used as input data. The modelling predicts that the pillar should be heated for 120 days with four 6.5 m electrical heaters with an effect of 200 W/m. The temperature increase in the pillar will then be approximately 60°C and the maximum stress on the hole walls will be approximately 160–170 MPa.

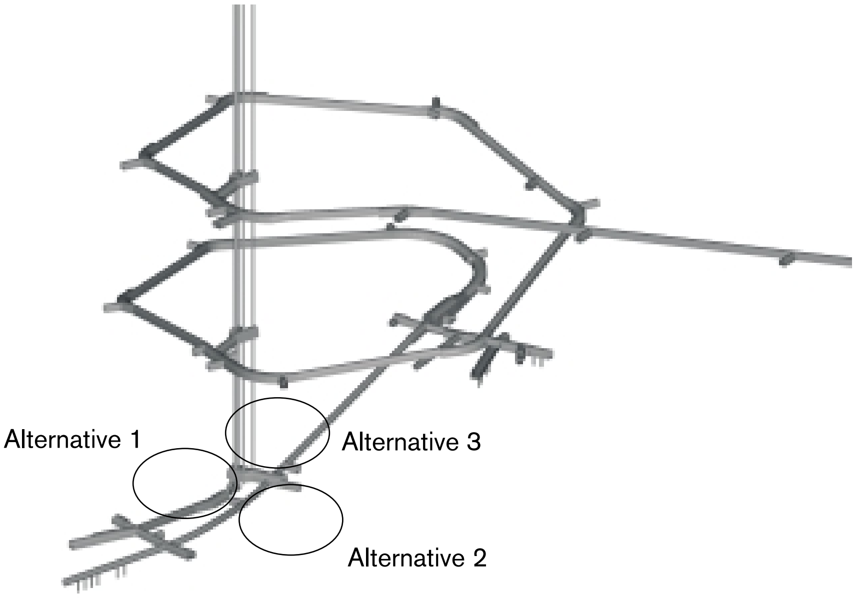


Figure 3-20. *The preferred site for the Äspö Pillar Stability Experiment at the 450 m level is Alternative 3 in the figure.*

The preliminary design and geometry of the monitoring equipment and pillar is shown in Figure 3-21.

The equipment to create the 1 MPa water pressure has been designed and ordered for pre-testing. The equipment consists of a rubber bladder with pressurised water stabilised by a steel lid at the top and bottom of the borehole connected by textile straps, see Figure 3-22.

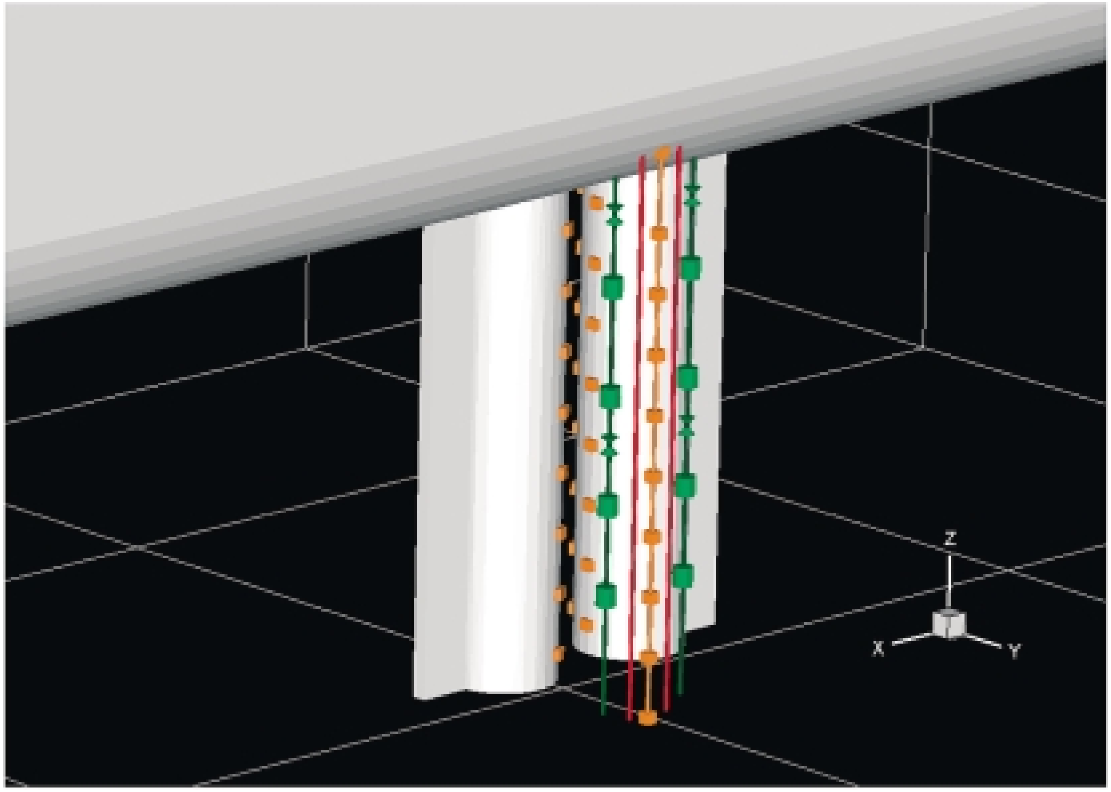


Figure 3-21. *Vertical view of the monitoring system at the proximity of the pillar. The thermistor arrays are the orange squares, the AE transmitters the green cones, the AE receivers the green cylinders, and the red vertical lines are the heaters.*

Figure 3-22. *The support of the rubber bladder to the left and the rubber bladder to be installed in the support once installed in the hole to the right. The picture of the rubber bladder is from the leakage testing at the manufacturing plant.*

3.8 Low-pH cementitious products

3.8.1 Background

It is foreseen that cementitious products will be utilised in the construction of the underground facility of the final repository for spent nuclear fuel. The long-term function and safety of the repository is quite dependent on the chemical conditions in the ambient rock. The use of standard construction cement paste will create pulses of pH in the magnitude of 12–13. Such high pH is detrimental and also complicates the safety analysis of the repository, as the effect of a high pH-plume should be considered in the evaluation. However, by using cementitious products that creates leachates below pH 11, these issues will never have to be resolved. Means to lower the pH are studied in order to decrease the initial peak in the leachate and to use silica to deplete the paste in Portlandite and lower the Ca/Si ratio of the cement paste in order to give a bulk paste with, for cementitious products, low pH. Adding of ultra-fine quartz also lowers the cement content. The Figure 3-23 outlines the safety assessors' view on pH in a deep repository as well as the principles for the pH-evolution for standard cement.

Use of low-pH cement is foreseen for applications like structural cast concrete, shotcrete, rock bolting and grouting. It might also be possible that cement is used as one of the constituents in the backfill material. SKB and Posiva launched a feasibility study in December 2001 to qualify low-pH cement for practical application when constructing the repository. In 2002 NUMO from Japan joined the project.

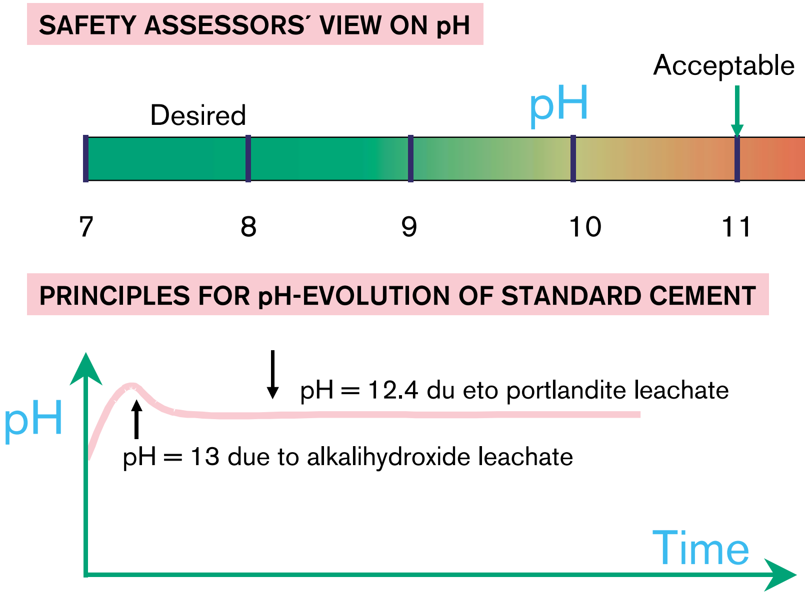


Figure 3-23. Safety assessors view on pH. Principles for the pH-evolution for standard cement and means to lower it below the target pH < 11.

3.8.2 Objectives

The original objectives were to:

- Achieve usable recipes of low-pH cementitious grouts for injection grouting and rock bolting.
- Test those grouts in a small field test.
- Compile influence of low-pH cement paste on function and safety of the deep repository.

3.8.3 Project work packages

The project is performed in seven different work packages (WP 1 to 7):

WP 1 deals with environmental impact and influence on repository long-term function and safety.

WP 2 deals with the basic understanding of low-pH cement paste and its interaction with the surrounding groundwater.

WP 3 deals with fabrication, e.g. grinding and mixing techniques of cement based material.

WP 4 searches for a low-pH rock bolt grout with suitable properties for rock bolting in practice.

WP 5 deals with low-pH rock bolt grouts for injection grouting aiming at recipes for grouts having acceptable penetrability.

WP 6 aimed at planning and execution of a small field-test, but was cut out from the projects for reasons presented below.

WP 7 includes planning of the next stage (large field-test) and project managing.

3.8.4 Results

It was more difficult than expected to find suitable injection grouts giving leachates with pH below 11. A small field test that was planned to take place during 2002 has therefore been cut out from the project and the focus is on finding suitable recipes for injection grouts.

For sealing of larger fractures and fracture zones, a co-ground cement and silica fume may be used. Cement based grouts for sealing of small aperture fractures is not yet available.

It is possible to make good low-pH rock bolt grouts with silica fume mixtures. Co-grinding of cement and silica fume gives stronger concrete and reduces the amount of super plasticizer needed. A problem identified on rock bolt grout is the autogeneous shrinkage, which can be close to 2 per thousand. This may, in the pessimistic case, give a crack aperture of 0.02 mm.

3.9 KBS-3 method with horizontal emplacement

3.9.1 Background

The KBS-3 method based on the multi-barrier principle is accepted by the Swedish authorities and the government as base for the planning of the final disposal of the spent nuclear fuel. The possibility to modify the reference method and make serial deposition of canisters in long horizontal drifts instead of vertical deposition of single canisters in the deposition hole has been considered since early nineties. The deposition process requires that each copper canister and its buffer material are assembled into a prefabricated perforated disposal container.

Late 2001 SKB published an R&D programme for the KBS-3 method with horizontal emplacement (KBS-3H), see Figure 3-24. The R&D programme /SKB, 2001c/ is divided into four parts: Feasibility study, Basic design, Demonstration of the concept at the Äspö Hard Rock Laboratory, and Evaluation.

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

3.9.2 Objectives

Most of the positive effects of a repository based on horizontal emplacement are related to the smaller volume of rock excavation. Positive effects are:

- Less environmental impact during construction
- Reduced impact on the groundwater situation in the bedrock during construction and operation.
- Reduced cost for construction and backfilling of the repository compared to KBS-3V. Great efforts are, however, required developing the variant.

The objective of the first part of the project, the Feasibility study, was to evaluate whether horizontal emplacement is a realistic alternative, and if so, to give SKB and Posiva a basis for continued evaluation of KBS-3H as a variant. The Feasibility study focused on differences compared to the reference concept KBS-3V. Highlighted tasks were excavation of deposition drifts, the deposition technique and the function of the buffer.

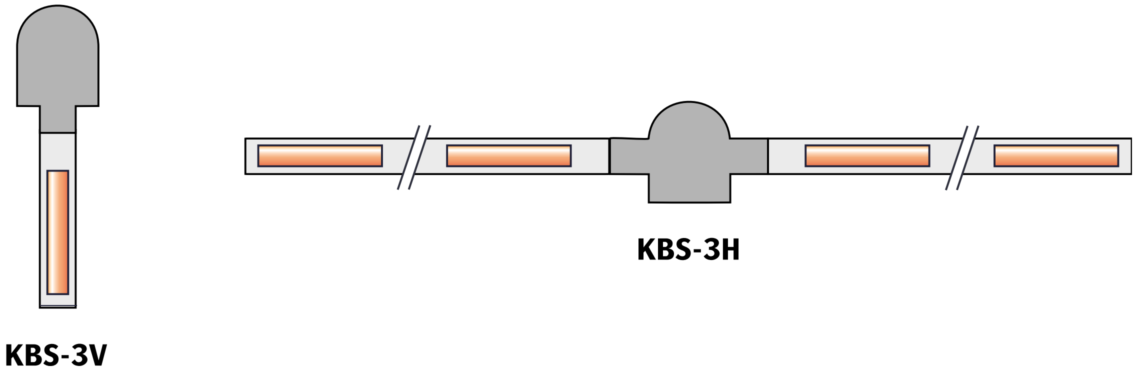


Figure 3-24. Schematic illustrations of variants of the KBS-3 method.

3.9.3 Results

The Feasibility study was finalised in October 2002 and reported to the SKB board in November. The results show that the KBS-3H concept is worth further development from a technical, economical and long-term safety point of view.

Different techniques for deposition of the prefabricated disposal container have been evaluated and a technique where air cushions are used in order to make the deposition process safe and efficient has been chosen for further development. Two different techniques for boring of the deposition drifts have been studied and evaluated, TBM and the so-called cluster technology. The performance of the buffer material has been studied and tested in experiments. Preliminary results indicate that the perforated disposal container does not affect the sealing ability of the buffer material negatively. Other experiments indicate that there is a significant risk of erosion of buffer material during certain circumstances. The knowledge about the performance of the buffer material is not complete and further studies are necessary.

A barrier performance safety assessment describing the differences with respect to buffer behaviour between horizontal and vertical emplacement was performed during 2002. It also identifies and describes the most important questions related to long-term safety to be solved within the R&D programme.

The decision to continue work within the R&D programme was taken by the SKB board in December 2002. The next phase in the programme is called Basic design and will be carried through in three different sub-projects during 2003:

- Technical development of the KBS-3H concept.
- Preparations for a future demonstration of the concept at Äspö HRL.
- Studies of the barrier performance of the KBS-3H concept.

Work includes manufacturing of boring equipment and initial tests. It also includes tests of the type of air cushion device planned to be used. Depending on the site chosen for the demonstration area it may be necessary to excavate a niche from which the demonstration deposition drifts will be excavated.

3.10 Cleaning and sealing of investigation boreholes

3.10.1 Background

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

Sealing of boreholes with cementitious materials is commonly used in construction work and can be performed with well-known techniques. Earlier studies, e.g. the Stripa project, have shown that sealing with cementitious material include a potential risk for degradation due to leaching and the sealing can not be guaranteed over time-periods longer than hundreds of years. Another opportunity is to use swelling clay materials, such as compacted bentonite blocks or bentonite pellets. Sealing with bentonite blocks has been tested in the framework of the Stripa project, in boreholes with a length of 200 m, with very promising results. A further development of this technique is however required to show that boreholes with lengths of up to 1000 m can be sealed.

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

3.10.2 Objectives

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

Phase 1 comprises:

- An inventory of known methods for sealing of boreholes with potential to be used for investigation boreholes. The inventory considers both cementitious materials and swelling clay materials.
- Performance of complementary laboratory experiments with sealing materials to obtain as high density and as low conductivity as possible.
- Investigation of the status of two instrumented boreholes at Äspö (KAS 06 and KAS 07).

Phase 2 comprises the following six issues:

I. Techniques for preparation of boreholes to be plugged. This issue comprises sealing and stabilisation of intersecting fracture zones, injection methods and packer techniques as well as identification and development of cement materials for minimum impact on smectite clay.

II. Selection of candidate plugging materials. Identification, development and testing of potential cement and clay materials and searching for other materials that can fulfil the criteria.

III. Selection of method for construction and application of plugs. Design of plugs with respect to borehole geometry, sealing rate and long-term performance.

IV. Performance assessment. Conceptual modelling of short and long-term performance of the plug. This issue also includes the planning of field tests.

V. Large-scale testing. Field tests of plug construction and performance.

VI. Evaluation, validation and assessment.

The work in Phase 2 will be made in two separate projects: Borehole cleaning (Issue I) and Borehole plugging (Issues II–VI).

3.10.3 Results

During 2002 work has been performed within Phase 1. A state of the art report summarising the developments of the sealing and cleaning techniques during the last 10–15 years has been put together. The report will be reviewed in the beginning of 2003 and printed thereafter.

Data from the two potential boreholes (KAS 06 and KAS 07) has been gathered to find out where in the holes the field tests can be performed.

3.11 Task Force on Engineered Barrier Systems

The Task Force on Engineered Barrier Systems focuses on the water saturation process in buffer, backfill and rock. Since the water saturation process is also a part of the modelling work in the Prototype Repository, the work is conducted under the umbrella of the Prototype Repository having the Task Force in a stand by position.

4 Äspö facility

4.1 General

An important part of the Äspö facility is the administration, operation, and maintenance of instruments as well as development of investigation methods. Other issues are to keep the stationary hydro monitoring system (HMS) continuously available and to carry out the programme for monitoring of groundwater head and flow and the programme for monitoring of groundwater chemistry.

The information group at Äspö is an important part in the process of creating a public acceptance for SKB's commission. This is done by giving information about SKB, the Äspö HRL, and the SKB siting process.

4.2 Facility operation

4.2.1 Background

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

The operation of the facility has worked smoothly. A number of new projects concerning safety, security and reliability have been initiated, started or completed during 2002.

The reliability of service in the facility and its underground-related systems (ventilation, hoist, lightning, pumps etc) has been almost 98% during 2002. The total energy consumption in the facility has decreased with 3.5% compared to 2001, despite the hot summer and an increase in number of personnel.

The service and maintenance agreement with OKG has been reduced and a number of small companies has taken over parts of the earlier agreement e.g. ventilation, cleaning, and refuse collection. The changes have meant lower costs and a higher degree of service. Certain parts of the facility operation have been taken care of internally, e.g. the maintenance of the green areas, plant supervision, and control.

4.2.2 Surface activities

The decision to host the staff of the site investigation project resulted in a need for additional office space besides the offices that were provided in the temporary barracks during 2001. The design of new offices in an extension of the ventilation building was initiated in February and the construction work started in September 2002. The extension is an additional floor hosting 22 offices and two conference rooms. The new offices will be completed in April 2003.

A new storage facility, for underground equipment, at the portal of the tunnel was completed and taken into use during spring. The construction of the store began in November 2001.

The access roads to Äspö have been improved. For example, road works have been performed on the road through Ävrö village and the bridge over Lindströmmen has been reinforced.

Uninterruptible Power Supply (UPS) was installed during spring 2002 with the aim to get a separate power supply for the computer severs. The above ground facility has now two separate UPS-systems, one for the computer servers and one for other critical systems e.g. switchboard, fire alarm, and operational supervision.

4.2.3 Underground activities

The long-term rock control and reinforcement programme, initiated in year 2000, has been continued to ensure safe and reliable conditions underground.

The facility operation monitoring system (ALFA) taken into operation during 2001 has been developed. The capacity was increased when the computer server was exchanged and the plant supervision system can now be reached via internet.

An automatic registration and object-monitoring system with the benefit to increase personnel safety underground was taken into operation for testing during 2002. Considerable problems with the system quality have delayed the project. The system will, however, according to present plans be taken into operation during 2003.

Work on increased fire safety underground has included an extension of the water distribution system at the 420 m level. More hydrate valves have been installed between the ground level and 220 m level. The new valves can supply more water. Safety-related education and fire fighting training of the personnel was held in accordance with present plans

Sump number 5 has been equipped with a spare circuit so that the underground facility can be pumped out even if a pipe in the hoist shaft breaks. The spare circuit has an outlet with valve at the 450 m level where a mobile pipe can be connected. The water can than be pumped to the closest sump above.

The ventilation system underground has been controlled with the aim to identify pressure reducing sections of the system. Measures will be taken to increase the air flux from 20 to 30 to m^3/s.

Parts of the underground roads have been improved with new asphalt covering.

4.3 Information and public relations

4.3.1 Background

SKB operates three facilities in Oskarshamn municipality, the Äspö HRL, CLAB and the Canister Laboratory. In 2002 SKB began site investigations including drilling of deep investigation boreholes at two sites, whereof one site is at Simpevarp.

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

4.3.2 Visitors and special events

During the year 2002, the Äspö HRL and the site investigation activities were visited by 9 775 visitors. The visitors represented the general public, communities, teachers, students, politicians, journalists, and visitors from foreign countries.

The total amount of visitors to all SKB facilities in Oskarshamn was 14 565. The information group at Äspö has administrated the visitors.

The U500 summer tours for the general public started in June and finished in August. The tours generated 1 804 visitors.

An annual event "The Äspö Day" took place on May 5. About 350 people took part in the underground tours.

On September 29 "The Geology Day" was celebrated in Sweden. SKB contributed by inviting the public to visit the drill site. Geologists and guides showed and explained how SKB performs site investigations. It was also possible for the visitors to bring their own piece of rock to SKB's geologists, to find out what kind of rock they have in their possession.

On December 8 an open house with the theme "Christmas in the Hard Rock Laboratory" was arranged. The open house generated 175 visitors.

4.3.3 Other activities

During 2002 the following improvements have been performed:

- The booking system has been constructed, implemented and is now running.
- A digital presentation has been produced. It is going to be implemented during 2003.

4.4 Hydro Monitoring System

4.4.1 Background

The monitoring of groundwater changes (hydraulic and chemical) during the construction of the laboratory is an essential part of the documentation work aiming at verifying pre-investigation methods. The great amount of data calls for efficient data collection system and data management procedures. Hence, the Hydro Monitoring System (HMS) for on-line recording of these data have been developed and installed in the tunnel and at the surface.

The HMS collects data of groundwater head, salinity, electrical conductivity of the water, Eh, and pH. The data are recorded by numerous transducers installed in boreholes. The system was introduced in 1992 and has evolved through time, expanding in purpose and ambition. The number of boreholes included in the network has gradually increased and comprise boreholes in the tunnel and in Äspö HRL as well as surface boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen and some boreholes on the mainland at Laxemar.

Weekly quality controls of preliminary groundwater head data are performed. Absolute calibration of data is performed three to four times annually. This work involves comparison with groundwater levels checked manually in percussion drilled boreholes and in core drilled boreholes, in connection with the calibration work.

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

4.4.2 Measuring system

To date the monitoring network comprises boreholes of which many are equipped with hydraulically inflatable packers, measuring the pressure by means of transducers. The measured data are connected to a central computer situated at Äspö village through cables and radio-wave transmitters.

4.4.3 Results

Improvements, new installations and other measures carried out during 2002 are:

- Installation of a new gauging box (MG0004G) located at the very bottom of the tunnel system and collecting water from the G-tunnel.
- Replacement of the remaining pressure transducers to ultrasonic transmitters in gauging boxes.
- The weirs and the sensors measuring electrical conductivity in the tunnel have been calibrated.
- Maintenance of the hydraulic multiplexer at 2162 m in the tunnel.

4.5 Programme for monitoring of groundwater head and flow

4.5.1 Background

The monitoring programme is a support to the experiments undertaken in the HRL and meets the requirements stipulated by the water rights court. The HMS implemented in the Äspö HRL and on the nearby islands is used to supply data to the programme for monitoring of groundwater head and flow.

The monitoring of water level in surface boreholes started in 1987 while the computerised 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. The tunnel excavation began to affect the groundwater level in many surface boreholes during the spring 1991.

To date the monitoring programme comprises a total of 127 boreholes (52 surface boreholes and 75 tunnel boreholes). Many boreholes are equipped with inflatable packers, dividing the borehole into different sections, and the pressure is measured by means of pressure transducers. Once a year, the data is transferred to SKB's site characterisation database, SICADA. Manual levelling is also obtained from the surface boreholes on a regular basis (once a month). Water seeping through the tunnel walls is diverted to trenches and further to 22 weirs where the flow is measured.

4.5.2 Objectives

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

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

4.5.3 Results

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

HMS data was 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 characterisation stage preceding the experiments. The number of information points is compiled in Table 4-1.

Table 4-1. Type of measurement and number of measurement points.

Type of measurement	Number of measurement points
Groundwater pressure in tunnel boreholes	209
Groundwater level in surface boreholes	83
Flow of tunnel water	22
Electric conductivity of tunnel water	11
Groundwater pressure in tunnel boreholes	209

4.6 Programme for monitoring of groundwater chemistry

4.6.1 Background

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

4.6.2 Objectives

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

4.6.3 Results

Groundwater samples were taken at one occasion during 2002, in October. Some project specific samples were taken in addition to the "monitoring samples". Sampling and analyses are performed according to SKB's routines (Chemistry Class no 4 and 5). The results from the sampling period in October have been distributed as a report to the parts involved and will also be reported in a summary report.

4.7 Geoscientific modelling

4.7.1 Background

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

In the GeoMod project the existing models will be updated by integrating new data collected since 1995. The major part of the new data has been collected during the Operational Phase for the different on-going experiments. The new data have been produced in the lower part of the Äspö HRL. The updated models focus on a volume including the tunnel spiral volume from about 340 m to about 500 m. In addition, the development of a geothermal model will be integrated in the project. This issue has earlier been run as a separate project.

4.7.2 Objectives

The objectives of the GeoMod project are to:

- Describe the geo-scientific properties of the rock volume containing the tunnel spiral.
- Identify relevant geo-scientific processes to explain the geo-scientific properties.
- Define the boundary conditions of importance to the rock volume processes.
- Develop the methodology to integrate the knowledge from different geo-scientific disciplines.
- Develop a coherent integrated geo-scientific model of Äspö.

The gathered geo-scientific information will be provided to ongoing and coming experiments at Äspö HRL as bases for e.g. the identification of suitable experimental rock volumes, and information for the setting of boundary conditions. The development and refinement of the methodology and the tools for construction of geo-scientific models may also be applicable for the geo-scientific characterisation of a future repository site.

5 International co-operation

5.1 General

Eight organisations from seven countries participated in the co-operation at Äspö HRL during 2002. The co-operation is based on separate agreements between SKB and the organisations in question. The participation by JNC and CRIEPI is regulated by one agreement and one delegate in the International Joint Committee represents the two companies. The agreements, which were ending in 2002, are re-negotiated, in US with USDOE instead of USDOE CBFO.

The international organisations are taking part in the experiments and projects described in Chapters 2 and 3. Several organisations are participating in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. In Table 5-1 the scope of each organisation's participation under the agreements is given. In the following sections some of the work performed by the international participants during 2002 is described in more detail.

SKB is through Repository Technology co-ordinating three EC-contracts and in addition, SKB takes part in several EC-projects of which the representation in five projects is channelled through Repository Technology, see Section 5.10.

Table 5-1. International participation in Äspö HRL projects during 2002.

Projects	ANDRA	BMWA	ENRESA	JNC	CRIEPI	NAGRA	Posiva	Sandia
Natural barriers								
Tracer Retention Understanding Experiment	X		X	X			X	
Radionuclide Retention Experiments		X						
Colloid Project		X					X	
Microbe Project		X						
Matrix Fluid Chemistry						X		
Task Force on Modelling of Groundwater Flow and Transport of Solutes	X	X	X	X	X	X	X	X
Disposal technology								
Prototype Repository (EC-project)	X	X	X	X	X		X	
Backfill and Plug Test			X					
Long Term Test of Buffer Material							X	
Low-pH cementitious products							X	
KBS-3 method with horizontal deposition							X	
Äspö Pillar Stability Experiment							X	

5.2 ANDRA

In 2002, ANDRA's implication in the Äspö HRL work comprised two aspects:

- Continuation of modelling contribution in site characterisation and approach of performance assessment with TRUE Block Scale and Task 6 of the Task Force on Modelling of Groundwater Flow and Transport of Solutes.
- New interest for engineered barrier systems expressed by joining the Prototype Repository project (with focus on the evolution of the buffer-backfill contact at the top of each deposition hole) and by designing a test on the bentonite buffer behaviour subjected to high temperatures, the Temperature Buffer Test.

5.2.1 TRUE Block Scale

2002 was the year of reflection on the results of TRUE Block Scale and of development of the reports which conclude the project. Within this framework, ITASCA took part in writing the final report on modelling of flow and transport. In complement, reflections were committed on the role of the "background fractures" in the radionuclide's retention processes and the means of integrating this question into the TRUE Block Scale Continuation project.

5.2.2 Task Force on modelling of Groundwater Flow and Transport of Solutes, Task 6

ANDRA is participating in Task 6 with the aim to gain experience on site characterisation and performance assessment modelling that are necessary for long-term safety assessment analysis. The major objective of Task 6 is to bridge the gap between site characterisation and performance assessment models. For ANDRA, three teams (CEA, Golder Associates and ITASCA) are carrying out modelling based on different approaches and numerical codes.

Task 6 incorporates four sub-tasks, which cover two spatial, and two temporal scales:

- Sub-task 6A: single fracture (10 m) and experimental time scale (months to few years).
- Sub-task 6B: single fracture and performance assessment (PA) time scale (10^7 years).
- Sub-task 6D: fracture network (100 m), experimental time scale.
- Sub-task 6E: fracture network, PA time scale.

Modelling work performed in 2002 concerns single fractures at both experimental and PA scales (sub-tasks 6A and 6B). Preliminary results were presented at the Task Force Meeting held at Äspö in June. Modelling effort focuses on studying the constraining power of the tracer tests.

A continuum approach was used for calculation of the groundwater flow field inside the single fracture plane representing Feature A. Heterogeneity of the fracture permeability field is analysed through a stochastic continuum approach based on description of the permeability field. Transport modelling was carried out as probabilistic sensitivity analysis. The parameters of the system uncertainties were described with ranges within which the parameters may vary.

Preliminary conclusions are based on the assessment of the constraining power of the HTO and strontium tracer tests. Diorite and mylonite parameters properties do not seem constrained by the test. It is likely that the short time scale of the experiment gives this result. The mass exchange with the inner zones is not significant during such a short time. HTO tracer test demonstrates weak constraining power of the fault gouge thickness and porosity. Filling material porosity was constrained by the HTO tracer. Dispersivity of the flow domain was also analysed and results demonstrated a weak constraining power for this parameter. The transport modelling does not show a constraining power as regards the flow wetted surface. Flow wetted surface, derived from the flow model, is the area on the fracture plane along which transport take place.

5.2.3 Temperature Buffer Test

ANDRA is in co-operation with SKB developing the Temperature Buffer Test (TBT). The test is dealing with the bentonite buffer behaviour under temperatures exceeding 100°C. The aim is to explore the temperatures limits, thus thermal power limits, under which thermally active wastes can be deposited in a repository without altering bentonite buffer properties.

TBT includes two canisters (each 3 m long and 0.6 m diameter) stacked in one deposition hole similar to those of the Prototype Repository (8.5 m deep and 1.8 m diameter). One canister is directly surrounded by bentonite and the other is separated from the bentonite by a sand shield.

During 2002, Clay Technology carried out the test design modelling, the acquisition of instrumentation sensors and the bentonite blocks fabrication. Aitemin conceived and built the twin heating canisters. SKB co-ordinated the project and carried out the fieldwork.

TBT will be implemented early 2003 in the Äspö HRL, in the same test area as the Canister Retrieval Test.

5.3 BMWA

The co-operation agreement between BMWA (Bundesministerium für Wirtschaft und Arbeit) and SKB was signed in 1995. Seven research institutes are performing the work on behalf of and funded by BMWA: BGR, DBETec, FZK, FZR, GRS, University Stuttgart, and TU Clausthal.

The objective of the co-operation in the Äspö HRL programme is to complement the knowledge on potential host rock formations for radioactive waste repositories in Germany. The work addresses groundwater flow and radionuclide transport, two-phase flow and transport processes, as well as development and testing of instrumentation and methods for detailed underground rock characterisation.

5.3.1 Prototype Repository

Experiments and numerical simulation of TH processes in the backfill

Laboratory experiments were performed to determine the thermal and unsaturated hydraulic properties of bentonite/crushed diorite mixtures. Water-retention curves were conventionally obtained from pressure cell and evaporation experiments (Figure 5-1).

In addition, transient data from heating and gas injection column experiments were analysed using inverse modelling techniques. Measured pressures, temperatures, and drained-water volumes were jointly inverted to estimate absolute permeability, thermal conductivity, specific heat, and capillary strength parameters. Simultaneous matching of all available data, specifically the gas breakthrough at the top of the column, proved difficult, pointing towards aspects of the experimental design and the conceptual model that need to be refined. The analysis of sensitivity coefficients and the correlation structure of the parameters revealed the importance of accurately capturing coupled thermal/hydrological processes within the column as well as the details of the experimental apparatus, such as heat losses and storage of water and gas in the measuring burette. The parameters estimated using different experimental and analytical procedures were consistent, providing backfill material properties that can be used for the simulation of gas and heat-generating radioactive waste repositories.

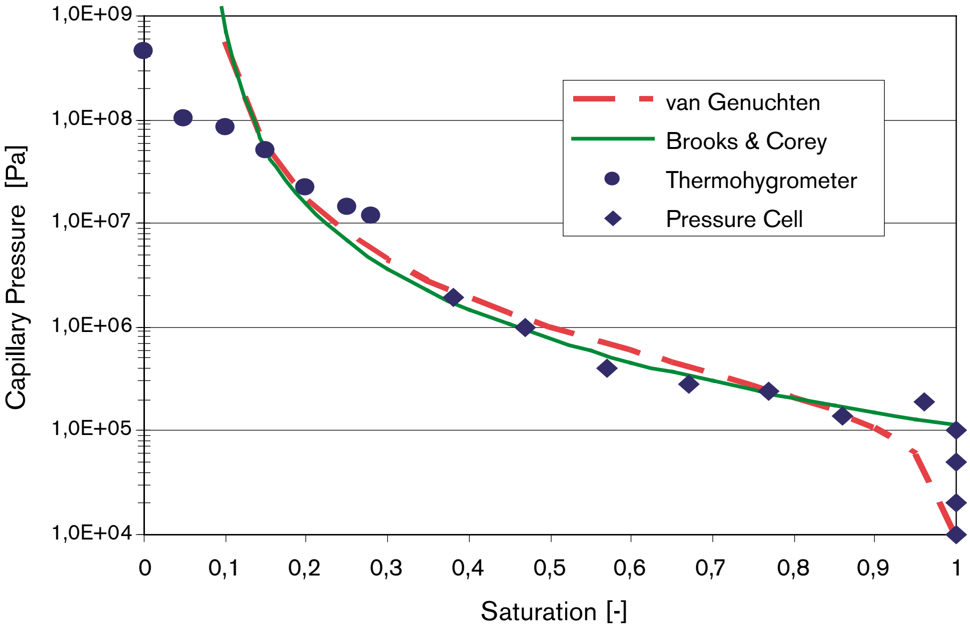


Figure 5-1. *Experimental capillary pressure-saturation data (symbols) and fitted Brooks-Corey and van Genuchten models (lines).*

Modelling of water saturation and mechanical stress

The saturation of the bentonite buffer in the deposition hole and the overlying tunnel of the Prototype Repository were calculated based on the "two-phase flow theory" taking into account the excavation disturbed zones. In the calculations, a saturation test was numerically reconstructed, *in situ* fracture mapping in the drift was checked, and surface packer tests were performed. The results, the measured water features in the deposition hole and the material behaviour of the bentonite, provide the basis for a numerical model. The model comprises 3D and 2D finite elements. The tests also included the buffer in the deposition hole, backfill in the tunnel, excavation disturbed zones (EDZs) ($w = 1$ cm; $K = 10^{-17}$ m^2) in the two cavities and two intersecting fractures. The model is coupled to the global hydraulic regime by the selection of hydraulic parameters. The mechanical stresses were calculated in parallel. The results of the hydraulic calculations and the water saturation of the bentonite were used to model the mechanical stresses. In the case of confined deformation in the margins of the deposition hole, the results indicate a build-up of stress from $P1 = -10$ MPa. In the case of non-confined deformation after total saturation of the bentonite, the largest principal stress decreased to $P1 = 0$ MPa and the two smaller principal stresses to $P2;3 = -5$ MPa. The influence of the variation of capillary saturation is apparent in the time range (5 to 30 years) until saturation.

For the theoretical case with hydraulic pressure of $P_w = 1$ MPa, saturation is basically completed after 10 years in the entire EDZ in the deposition hole. In a more realistic case with water inflow via a fracture and several other locations, saturation is after 30 years still below $S_w = 80\%$ at the point in question. (Figure 5-2).

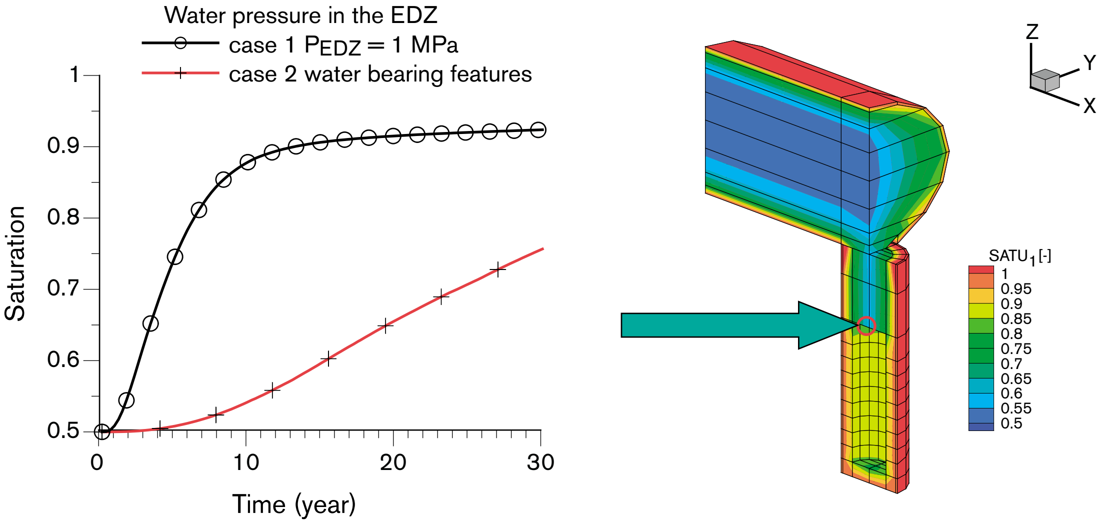


Figure 5-2. *Water saturation versus time for load cases.*

Temperature distribution

ROCKLOW, a finite element program system, was used to calculate the temperature distribution (Figure 5-3). The 3D modelling of half the test site takes into account the thermal conductivity (λ), the specific heat capacity (c_s) of the individual materials, and the time sequence of heat inflow.

Modelling the migration of nuclides through the bentonite after the assumed hypothetical failure revealed different breakthrough curves for the three analysed nuclides ^{241}Am, ^{137}Cs, and ^{90}Sr. The influence of diffusion and radioactive decay declines considerably if sorption is taken into account.

Geoelectric monitoring

In the Prototype Repository project electrical resistivity measurements will be conducted in boreholes and backfilled tunnel sections in order to investigate time-dependent changes of water content in the buffer, the backfill, and in the EDZ. In these investigations advantage is taken of the dependence of the electrical resistivity of geomaterials on their water content. In order to enable correlation of the measured resistivity with the actual water content, laboratory calibration measurements were performed in the geotechnical laboratory of GRS in Braunschweig/Germany.

The measuring programme, agreed by SKB and GRS, includes the monitoring of two electrode arrays in the backfilled tunnel above the deposition boreholes, three electrode chains at top of deposition hole 5 and three electrode chains in the rock between deposition holes 5 and 6 (Figure 5-4).

Special pressure-watertight cables and connectors were selected to connect the electrodes to the geoelectrical monitoring system which was installed in the data acquisition room in the G-tunnel.

The electrode array in the backfill in the inner section (Section I) was installed in October 2001 and the measurements were started immediately after completion of drift backfilling. The electrodes in the three boreholes in the rock between deposition holes 5 and 6 were installed in 2002. Continuous measurements are performed since August 2002.

The remaining electrode arrays in the buffer at top of deposition hole 5 and in the backfill in the outer section (Section II) will be installed in April and June 2003.

Results from measurements in the backfill in Section I

The resistivity distribution in the areas between the chains is determined by means of tomographic dipole-dipole measurements. The recording unit for these arrays is controlled remotely from Braunschweig/Germany via a telephone connection which allows daily measurements. From the measured apparent resistivity values the "true" resistivity distributions in the different parts are computed applying the latest inversion software. Monthly calculated inversion data for the different arrays are provided in quarterly data reports in the form of tomograms. Additional data for smaller time periods can be made available on demand.

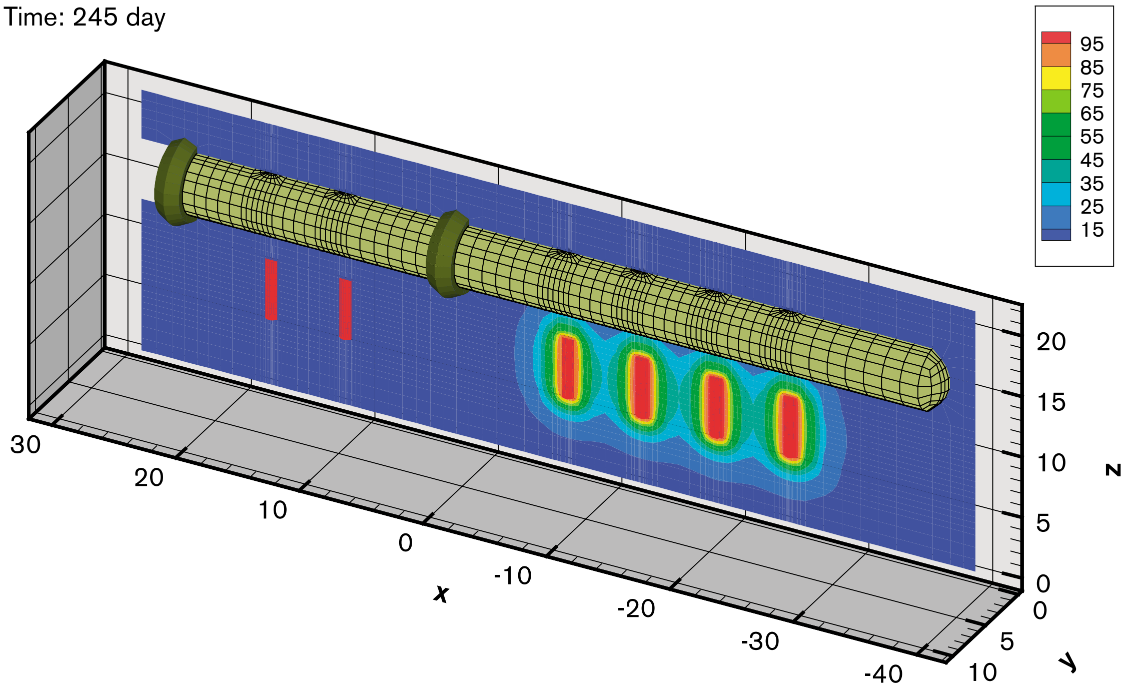


Figure 5-3. Temperature (°C) distribution in the Prototype Repository after 245 days.

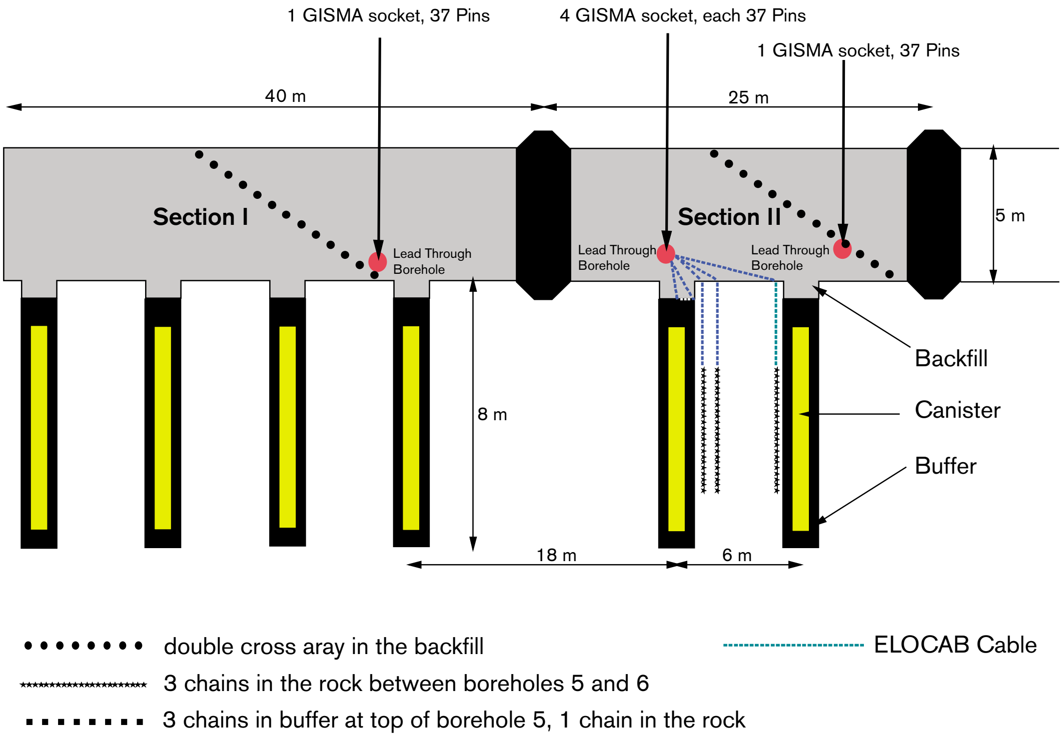


Figure 5-4. Arrangement of electrode arrays in the Prototype Repository.

The initial resistivity value of the backfill in October 2001 (Figure 5-5) was about 10 to 14 Ωm corresponding to a water content of 13 to 14%. In the following months the resistivity decreased due to water uptake from the rock to about 7 to 10 Ωm (Figure 5-6) which corresponds to a water content of about 14 to 16%. Water uptake seems to continue until the end of 2002, especially at the drift wall, where values of about 6 Ωm were determined, indicating a water content of 16 to 17%. This process continued to the middle of the drift, indicating further moisture uptake in the centre of the backfill until November 2002.

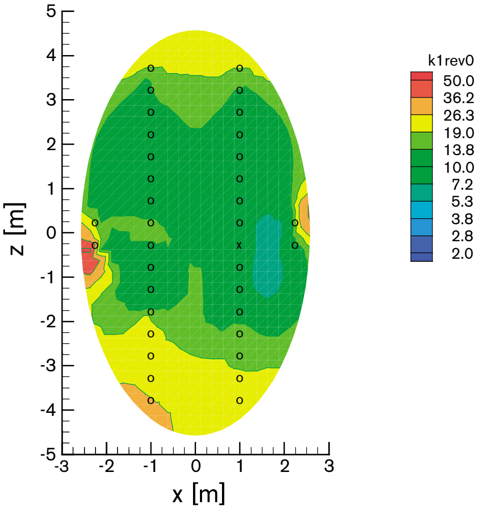


Figure 5-5. *Resistivity distribution in the backfill in Section I on 27 October 2001.*

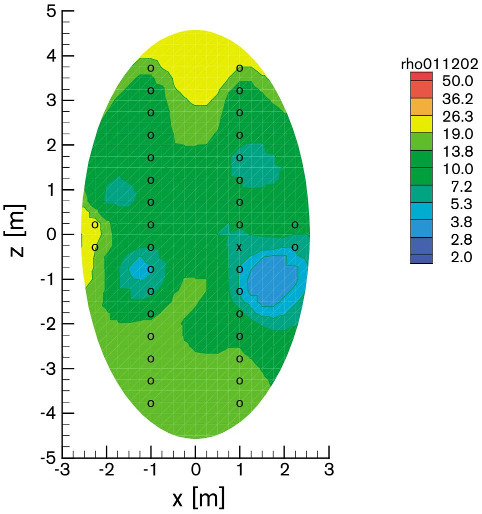


Figure 5-6. *Resistivity distribution in the backfill in Section I on 2 December 2001.*

Results from measurements in the rock in Section II

The resistivity distributions along the three electrode chains installed in the rock between deposition holes 5 and 6 are quite similar to each other and, as can be expected, show no variation in time, see Figure 5-7 and Figure 5-8. Close to the electrodes, the resistivity ranges around 200 Ωm. This value characterises the water-saturated concrete used for backfilling the electrode boreholes. Farther away from the boreholes, the resistivity rises to values of 2000 to 7000 Ωm which is characteristic for water-saturated granite.

It is of special interest whether the emplacement of the bentonite buffer in deposition holes 5 and 6 in 2003 will lead to a desaturation of the rock due to spontaneous water uptake from the rock because of the very high suction of the bentonite.

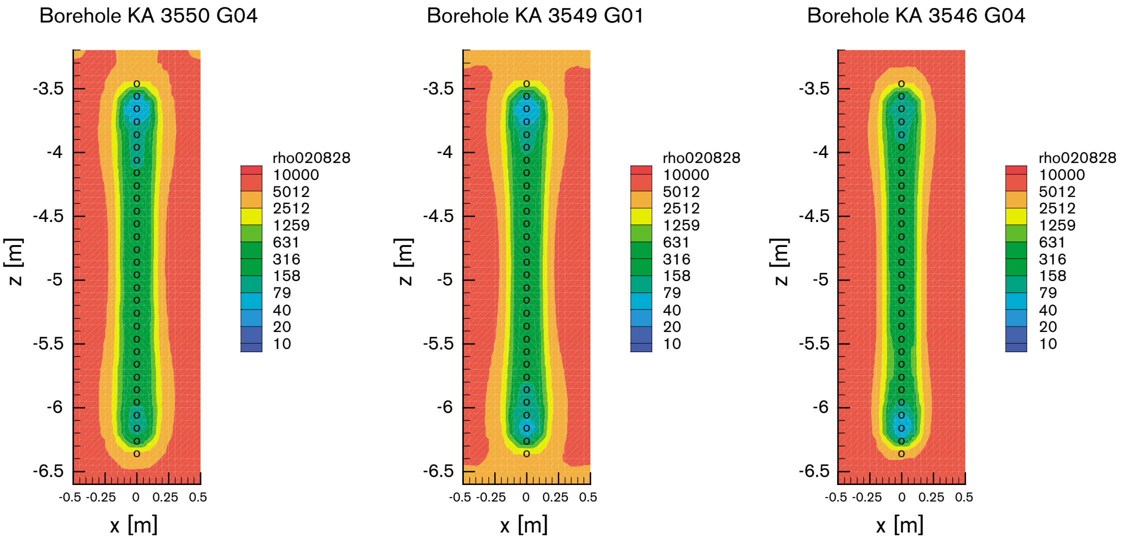


Figure 5-7. Resistivity distribution along electrode chains in the rock on 28 August 2002.

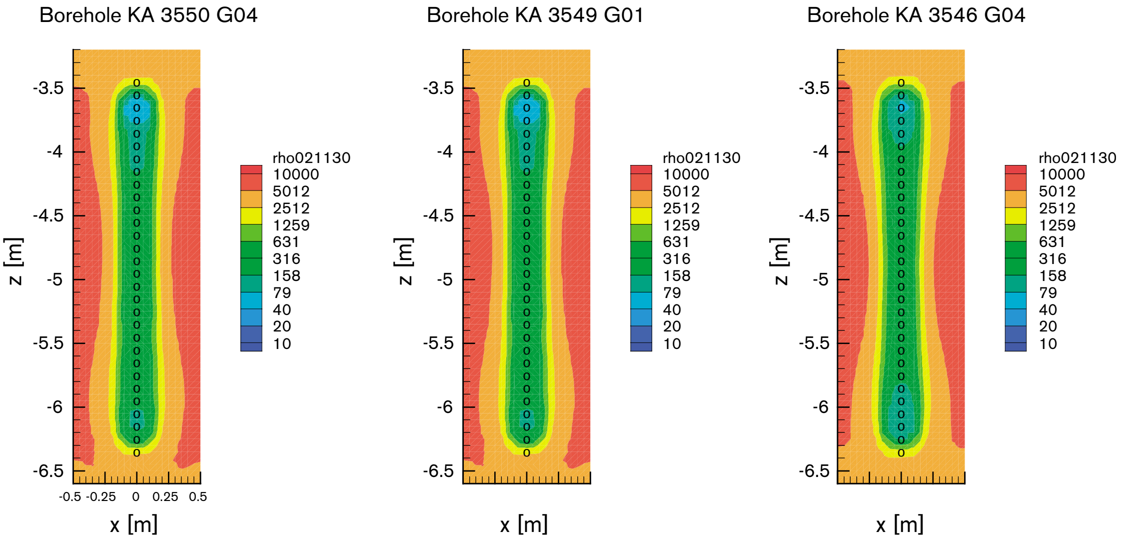


Figure 5-8. Resistivity distribution along electrode chains in the rock on 30 November 2002.

Calibration of the relation between resistivity and water content in the rock

Evaluation of the resistivity measurements in the rock around the deposition holes requires calibration measurements on the relation between resistivity and water content independence of the temperature. These measurements were performed at ambient temperature, at 35°C and 70°C. Different saturations were generated by drying completely saturated specimens in air, under vacuum, and by heating. The resistivity of the samples was measured using the two-point method by applying a known current to the head planes of the sample and measuring the resulting voltage drop over the sample length.

The results show that the resistivities of the granitic rock increase with decreasing saturation. The measured resistivities range between 2218 Ωm up to 10 588 Ωm at full saturation and between 105 900 Ωm up to 530 294 Ωm at low saturation. The results are presented in Figure 5-9. At saturations between 20% and full saturation, the influence of the temperature is not significant. Only at saturations below 20% a difference between the resistivities at 20°C and those at elevated temperature can be observed. At higher temperature only a slight increase in resistivity was measured. This observation is in contrast to the results of the backfill, where the resistivities were lower at higher temperatures because the conductivity of most electrolyte pore solutions increases with increasing temperature. Due to the very small pore spaces of the granite, it is possible that higher temperatures lead to a reduction of ion mobility.

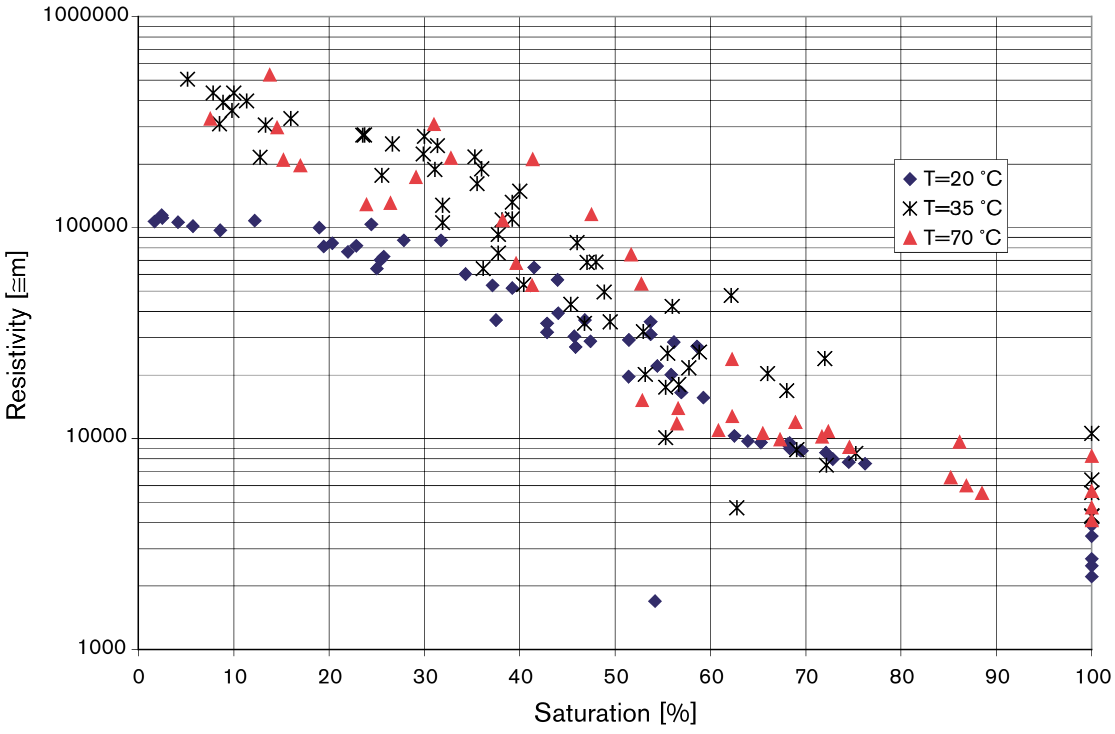


Figure 5-9. *Resistivity of granite at different saturations and temperatures.*

Modelling the resaturation of bentonite

Participation in the modelling working group of the Prototype Repository aims at creating a simplified model for simulating resaturation in view of a long-term safety assessment for final repositories.

Two one-dimensional codes for modelling resaturation have been developed in an earlier project phase. The first model, called advection model, is concerned with simulating resaturation with liquid water and is based on a new conceptual approach. Darcy flow in the pore space caused by hydraulic pressure and suction pressure as well as changes of the pore volume due to a fast hydration is considered in the model. The second model, called vapour diffusion model, simulates resaturation with water vapour, taking only binary gas diffusion and pore volume changes by hydration into account. Both numerical models have been introduced and discussed in the framework of the Prototype Repository modelling group as well as on the workshop on clay microstructure which was co-organised by SKB.

The advection model was checked using a one-dimensional water uptake experiment in which the water uptake of the specimen was measured as a function of time. The water content of the specimen was determined by experiment and was also calculated by the advection model and by the well-known empirical diffusion model as a reference model, see Figure 5-10. The time dependent inflow rates as well as the position of the moisture fronts were calculated by both numerical models but not measured in the experiment. The position of the moisture front in the diffusion model is here defined as the location of 50% water saturation. Figure 5-10 shows clearly that water uptake under simple conditions can be described both by the advection model and by the empirical diffusion model.

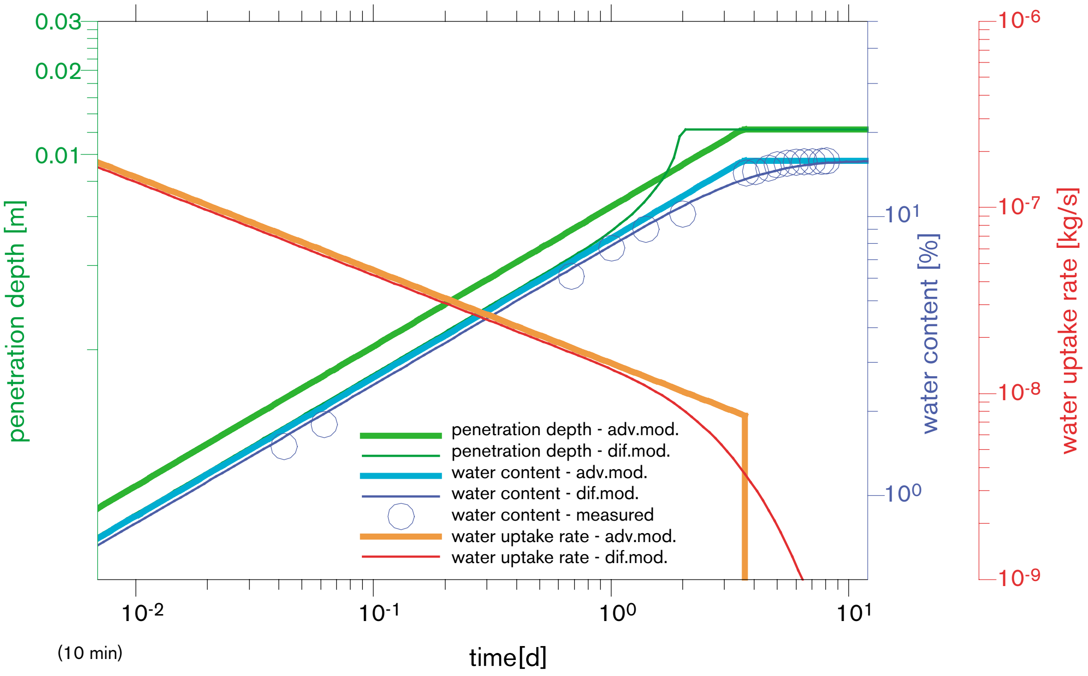


Figure 5-10. *Results of the new advection model, the empirical diffusion model and the measurements.*

In order to choose an appropriate value for the permeability of MX-80 at water saturation the literature was searched. The data were transformed where necessary to fit into a diagram of permeability versus dry density. The obtained data points lie mostly within a rather small band and thus represent a trustworthy source for future modelling exercises (Figure 5-11).

The main difficulty concerning the vapour diffusion model is the hydration which controls the porosity changes as a direct consequence of the loss of vapour from the pore space. The central parameter is the rate at which vapour is drawn from pore space and integrated in the interlamellar space of the clay particles. To evaluate the hydration rate, orientating lab experiments have been performed at GRS. Based on these data a desk study using the vapour diffusion model was performed. The results with varying hydration rates indicate that hydration with water vapour is a significant resaturation process.

In order to investigate the time dependent moisture distribution, supporting laboratory experiments were performed for uptake of Äspö-water. The analyses of the data as well as a rerunning of the tests with an atmosphere of highly saturated water vapour instead of liquid water are to be executed in 2003.

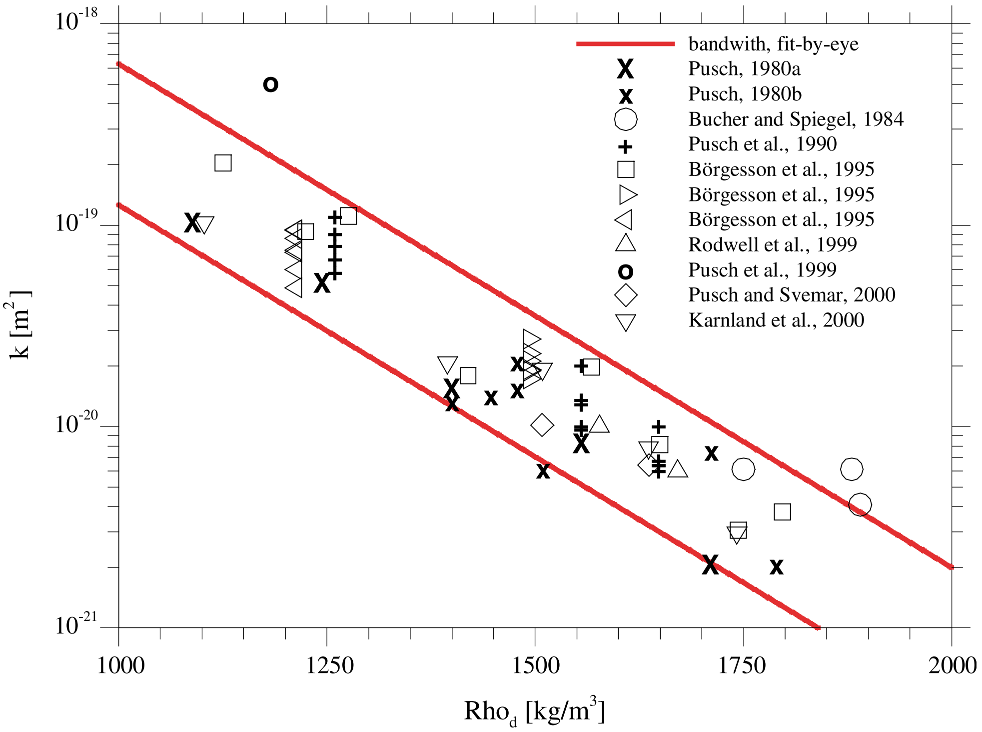


Figure 5-11. *Compilation of permeability data for MX-80 (literature survey).*

5.3.2 Radionuclide Retention Experiments, migration of actinides

The FZK-INE investigations are focusing on sorption and migration of radionuclides, especially actinides, in fractured rock. To guarantee undisturbed groundwater conditions, the experiments are designed to be compatible with the CHEMLAB 2 probe. The objectives of the experiment are directed to the applicability of radionuclide retention coefficients measured in laboratory batch experiments for *in situ* conditions, the validation of radionuclide retardation measured in laboratory by data from *in situ* experiments in rock, and the reduction of uncertainties in the retardation properties for americium, neptunium, and plutonium.

Experiments and results

An *in situ* migration experiment was started in November 2001. As a low flow rate of 0.3 ml/h was selected, the duration of this experiment was scheduled for 3 month. Due to a failure of the CHEMLAB 2 probe, the experiment was interrupted during the actinide cocktail injection phase. As a consequence, it required some time to readjust the CHEMLAB probe. A new *in situ* experiment was planned to be started in November 2002.

Meanwhile, at INE, a series of 3 new drill cores were prepared. The internal structures of the embedded drill cores were investigated by means of X-ray tomography. From the tomography data, a three dimensional (voxel) representation of the flow path was constructed (Figure 5-12). The hydraulic characteristics of the fractures were determined by tracer tests using HTO as a non-sorbing conservative tracer. Both data sets will be used as a basis of forthcoming work to the development of a transport modelling approach appropriate to describe the measured actinide migration.

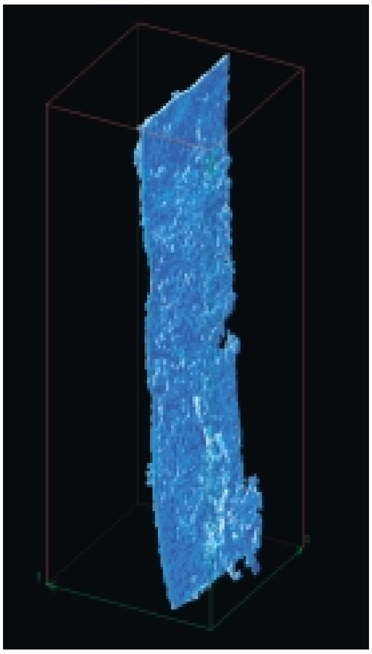


Figure 5-12. *3D (voxel) representation of a fracture in Core #5 determined from X-ray tomography data. Core #5 prepared for an* in situ *experiment in November 2002.*

After termination of the migration experiments, the embedded cores were cut perpendicular to the cylinder axis into slices with a thickness of 4 mm. Abraded material was dissolved and analysed with respect to the injected actinides and natural uranium and thorium by means of ICP-MS. The slices were scanned by means of an optical scanner using a resolution of 600 x 600 pixels per inch. The radioactivity retained in each slice was determined by spatial resolved radiography (Cyclone Phosphor Scanner, Packard BioScience, Dreieich, Germany) at the same resolution. γ-scanning (γ-detector by Canberra, Eurisys GmbH, Germany) for the 74.4 keV lines of ^{243}Am and the 312 keV line of ^{233}Pa daughter of ^{237}Np allowed quantification of sorbed actinides.

From these measurements, the retention mechanism could be deduced: In the cocktail injected into the cores, the actinides were present as Am(III), Pu(IV) and Np(V). Comparisons between the actinides show that all actinides are retained in the same locations. Am (III) is the most stable redox state of this element. For this reason, one can assume that retention of Am does not depend on reduction/oxidation processes. The redox state of Np was analysed in two slices. Np was dissolved with HCl, and by TTA (thenoyltrifluoroacetone) extraction Np(IV) was separated. As a result, it was found that more than 60% of Np was bound to the slices in the form of Np(IV). Np(V) in solutions, even at negative Eh (e.g. in the cocktail) remained as Np(V) for many months as long as no solids were present. This indicates that solid granite and/or fracture filling material catalyses reductive processes. Potential sites for reduction processes might be pyrite and Fe(II) containing clay minerals which are detected in the Äspö granite.

One can assume that in the pH and Eh range measured in the CHEMLAB drill hole Pu can exist in two redox states both as Pu(III) and Pu(IV). If Pu is reduced to trivalent state, a sorption behaviour similar to that of Am(III) can be expected. In the trivalent state, solubility limit of Pu should not play any role under these conditions.

5.3.3 Colloid Project, background measurements

In safety assessment for a repository of radioactive waste, aquatic colloids existing in natural water play a role as carrier for the migration of radionuclides, mainly actinide ions from the waste to the biosphere. Apart from actinide oxide/hydroxide colloids, colloids released from backfill bentonite and background colloids present in natural groundwater are of particular importance. In this study the amount of background colloids in natural groundwater in the Äspö HRL granite formation is determined. The aim is to investigate the colloid occurrence in different groundwater types without any interferences by sampling.

Experiments and results

The Laser-Induced Breakdown Detection (LIBD) has been developed for the ultra-trace detection of colloids. The advantage of this method is a several orders of magnitude higher sensitivity, particularly for colloids with a size < 100 nm. A mobile LIBD setup, particularly designed for *in situ* measurements and equipped with a new high-pressure flow-through detection cell (Äspö hydrostatic water pressure: maximum 35 bar) is used. This detection cell is directly connected via plastic tubing to instrumented boreholes containing sampling sections for the groundwater. At depths from –70 m down to –416 m, eight types of representative groundwater with compositions typical for their origin, e.g. meteoric, Baltic Sea, and glacial, are analysed. The results are described in the preceding Äspö HRL Annual Report /SKB, 2002/.

The findings from the *in situ* colloid detection campaign are evaluated and some consequences are drawn for further experiments. It is shown during the evaluation process that *in situ* measurements of pH and Eh are required. Consequently, a device for these measurements under elevated hydrostatic pressure is under construction and will be tested in the near future.

5.3.4 Transport and retention of repository-related elements in micro-fractured rocks from the Äspö HRL

The migration of undersaturated solutions in open fractures is the dominating process of spreading repository-related pollutants in granitic rocks. This process is a combination of two limiting cases: (i) The migration of solutions with high transmissivity and low water-rock-interactions in widely opened fractures, and (ii) the migration of solutions within the rock matrix at very low transmissivity and extensive exchange reactions between rock and migrating water.

Experiments and results

This project is an attempt to describe processes of migration and retention of trace elements in the transitional zone between large fractures and undisturbed rock. The approach is based on the idea of a dendritic distribution of micro-fractures with continually decreasing widths and abundances (Figure 5-13). In order to characterise the retention of pollutants in fractured Äspö granitoids the following investigations were performed:

- Determination of the distribution and interconnectivity of micro-fractures as well as fracture surface areas and porosity as a function of the distance from highly transmissive fractures (by computerised X-ray tomography (CT) and microscopy).
- Experiments carried out to determine the retention capacity of mineral assemblages occurring on fresh (newly formed) and older fractures. They include those of altered Småland Granite and unaltered Äspö Diorite, clinochlore and ordinary chlorite, as well as AlOOH and SiOOH material. The experimental solutions were equivalent to currently migrating underground solutions of the HRL Äspö.

A large diversity was observed for the spatial distribution of micro-fractures in the drill cores selected for this study. Visualisation of the fracture distribution by CT is limited by the resolution of the method; fracture widths below 40 µm cannot be determined accurately. The resolution of UV and conventional polarising microscopy allows a far better resolution, but the volume of fractured rock to be analysed is comparatively small. Based on a large number of thin sections cut from selected drill cores, the total porosity caused by fractures ranges from 0.002 to 1.0%. An evaluation of the trace length of fractures observed in thin sections yields a total surface area of 10 200 mm^2 per 100 cm of core length. The total porosity caused by fracture propagation, however, cannot be related directly to the surface area.

The mineralogy of the fracture systems investigated principally may be divided into two different types: (i) newly opened (recent) fractures exhibit the rock-forming minerals of the matrix without additional secondary minerals, (ii) older fractures are covered by assemblages of chlorite, epidote, calcite, quartz, and minor amounts of fluorite, baryte, prehnite etc. The thickness and the degree of smoothing of former irregular morphologies depends on the time span the surfaces were subjected to migrating underground solutions and, thus, to continuous precipitation of fracture fillings.

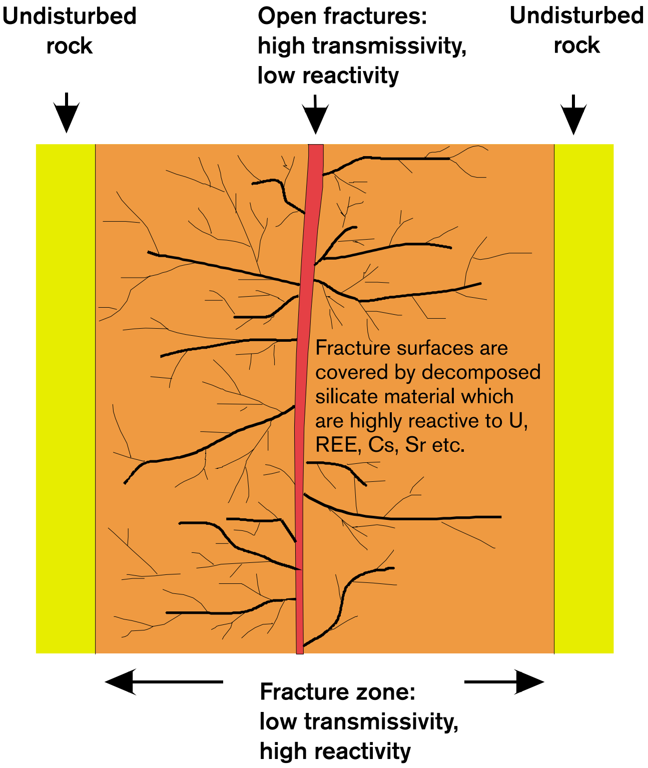


Figure 5-13. *Basic model of dendritic penetration of micro-fractures from high transmissive fractures into the rock matrix. Occurrence and opening widths of micro-fractures decrease with increasing distance.*

Based on these observations, two different types of experiments were performed to ascertain the retention capacity of fracture surfaces for pollutants. For the case of recently opened fractures, crushed altered Småland Granite and fresh Äspö Diorite were subjected to underground solutions containing 800 ppb each of Co, Sr, Cs, Ba, La, Nd, Yb, Th, and U. The retention capacities for these elements were calculated from the specific uptake of elements on the rock surfaces (retention capacity) and the total surface of the solid materials. The results for Äspö Diorite and for Småland Granite are very similar: For Co, Sr, Cs, and Ba the retention for 1 m^2 of fresh fracture surfaces is in the range of 300 to 420 µg, for Y, 80 to 90 µg, and for La and Nd, 6 to 9 µg. The experimental determination for Th and U failed due to precipitation problems in the starting solutions at pH ranges prevailing in the HRL. In an additional set of experiments, the uptake of the above named elements by the abundant fracture phases chlorite and clinochlore yields a significant uptake of Co and Cs.

These results may be applied to the fracture surfaces measured here. However, the validity of such calculations distinctly depends on the quality of the data base for a large volume of granites in the vicinity of main fractures systems. Thus, the data base for fracture surfaces needs to be expanded significantly before the retention capacities reported here are applied to a larger volume of Äspö granitoids.

5.4 ENRESA

Within the frame of the collaboration agreement signed between ENRESA and SKB the demonstration projects Backfill and Plug Test and Prototype Repository, conducted at the Äspö Laboratory, are of especial interest to the former. Both projects pertain to crucial issues related to the global performance assessment of a repository in granite, the KBS concept. Although the Spanish reference concept differs from the Swedish in some aspects, mainly configuration and site specific characteristics, both concepts have some common features. The experiences and lessons learned in tests related to one concept can be easily extrapolated to the other.

For those reasons ENRESA is actively involved in both projects providing SKB with technical and scientific support in certain tasks. The contribution of ENRESA to the above mentioned projects seeks the following objectives.

Backfill and Plug Test:

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

Prototype Repository:

- Monitoring potential movements in the canisters as a consequence of buffer hydration.
- Development and application of conceptual and mathematical models for predicting and evaluating the evolution of the engineered barriers as pertain to fully couple thermo-hydro-mechanical processes as well as partially coupled chemical processes.

5.4.1 Backfill and Plug Test

Local permeability measurements

A dynamic pore pressure (DPP) sensor is a specially constructed hydraulic piezometer, with a cylindrical ceramic filter of 60 microns pore size, including a miniature pressure sensor inside. Each piezometer has two metallic capillary tubes for water input and output, and an electrical cable for the pressure transducer signal.

The DPP sensors work in the same way as the "piezocone" testing method: a controlled positive pressure pulse is applied to the sensor and the evolution of the pressure drop in the sensor body, which depends on the local permeability of the surrounding material, is analysed.

In 1999, 13 DPP sensors were installed in some areas of section A4 of the backfill (Figure 5-14), where a higher density gradient may be expected (i.e. rock proximity). The goal is to compare the local permeability values obtained from the DPP with the global value estimated by back-analysis from the flow test to be performed when saturation is attained.

Figure 5-14. *DPP sensor installed close to the rock face.*

Once saturation is reached, a water pulse will be applied on each DPP and the corresponding dissipation time measured. The soil permeability is then calculated from the shape of this dissipation curve.

The entire measurement sequence is carried out manually, although some of the operations are automated (special valves control) to simplify the process, making it more accurate and repetitive, and to avoid miss functioning. Data is being automatically recorded.

Measurements from all sensors are stored in the database every 10 minutes, except when a test pulse is performed in which case readings are stored every second.

Work performed and results obtained

The activities carried out during 2002 were the following:

- Maintenance of the installation, remote monitoring, and data archiving.
- Functional check of the pulse test devices.

A check of the equipment installed at Äspö to perform local pulse tests was performed during December 2002. A first inspection showed that at least 9 devices were measuring positive pore water pressure. Some pulses were applied to 4 circuits for checking the whole equipment. The results showed that after 4 years of backfill hydration the dynamic pore pressure sensors and all the basic equipment (PC, de-air water reservoirs, valves, etc) were operative. During 2003 it is expected to perform all the pulse tests required to analyse the local hydraulic conductivity of the backfill.

Modelling and supporting laboratory tests

The formulation used for the modelling work is a fully coupled combination of a pre-existing code, CODE_BRIGHT, to solve non-isothermal multi-phase flow of brine and gas through deformable and unsaturated saline media problems and the reactive transport equations. In this formulation it is considered that geochemical variables, such as osmotic suction and concentration of chemical species in the liquid and solid phases, can affect the hydro-mechanical behaviour of clayey soils.

For the simulation of the hydration process of the backfill only the hydro-chemical problem is considered. The temperature is assumed to be constant. The gas phase has not been taken into account. The main processes considered are:

- Advective flow of water and solutes (Darcy's law).
- Molecular diffusion of solutes (Fick's law).
- Mechanical dispersion of solutes (Fick's law).
- Ion exchange of Na^+ and Ca^{2+}.

Osmotic gradient due to different salt-water concentrations in mixing water and hydration water has been neglected in this analysis.

The geochemical model considered is a preliminary approach where only the species NaCl and $CaCl_2$ are taken into account.

The analysis required some additional information to express the coupling between hydraulic conductivity and salt concentration. The influence of salinity on the saturated hydraulic conductivity has been studied by means of oedometer tests carried out in Rowe cells. The influence of salinity on the unsaturated hydraulic conductivity has been analysed by means of water uptake tests. The main drying and wetting retention curves used in this work were obtained in a mixture of bentonite and sand (due to the big size of the crushed granite). Apart from the tests indicated above, Clay Technology performed some water uptake experiments using different salt concentrations for the hydration water.

Work performed and results obtained

A numerical simulation of the flow tests has been performed during 2002 to identify the critical parameters of the problem and to support the final definition of the test protocol. Section A4 has been considered as a base geometry in these analyses. A flow test will involve a decrease of the pore water pressure in one mat while keeping the initial water pressure (500 kPa) at the other mats. Because of the geometry conditions, flow between mats is mainly one-dimensional. The code CODE_BRIGHT has been used to simulate the whole hydration process. The situation by the end of 2002 is close to saturation, but the numerical analyses show that some areas of the backfill could still be unsaturated. The analyses are very sensitive to the compressibility of the backfill and to the initial conditions obtained when the material was compacted.

Figure 5-15 presents the computed profile of degree of saturation between the mats limiting section A4 (points A and B are located in the central part of each mat). It has been assumed a Young's modulus of 500 MPa and different values for initial matrix suction. In all cases the saturation in the central part of the backfill is greater than 80%. Although this result indicates that the backfill is in fact almost saturated, the scattering might forecast unexpected delays when performing the global flow tests. When the pore water pressure is changed on one mat a transient flow is produced. The steady state situation is reached after certain time, depending on the backfill initial conditions. Figure 5-16 shows the evolution of the water flow rate at mat D4 for the six different values of initial matrix suction. It can be observed that if the backfill is not fully saturated (i.e. if initial suction was 2.3 MPa) the time required to start collecting water is about 100 days. Therefore, the steady state conditions in a global flow test are very difficult to predict in this simulation, since the results are very sensitive to the initial conditions and those have some scattering due to the nature of the backfill. The global flow tests may be used to reduce some of the uncertainties linked to the characteristics of the material and its compaction.

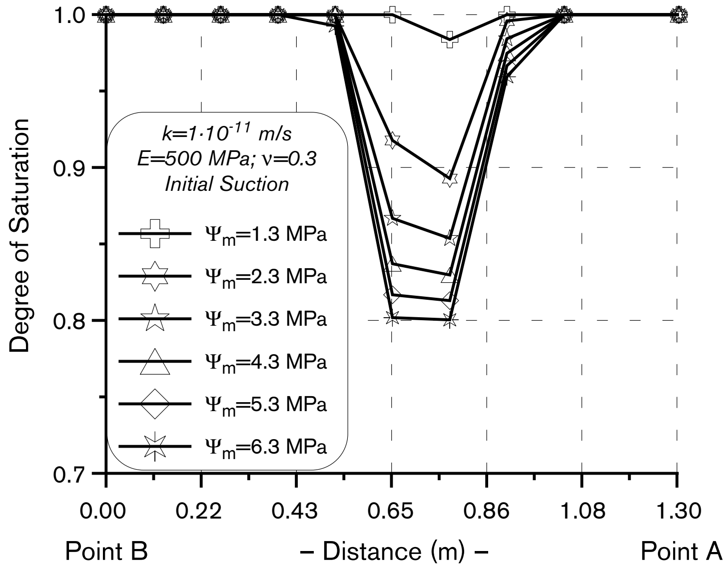


Figure 5-15. *Backfill degree of saturation profile between the two mats limiting section A4 in its central part, after 1480 days from the beginning of the hydration process.*

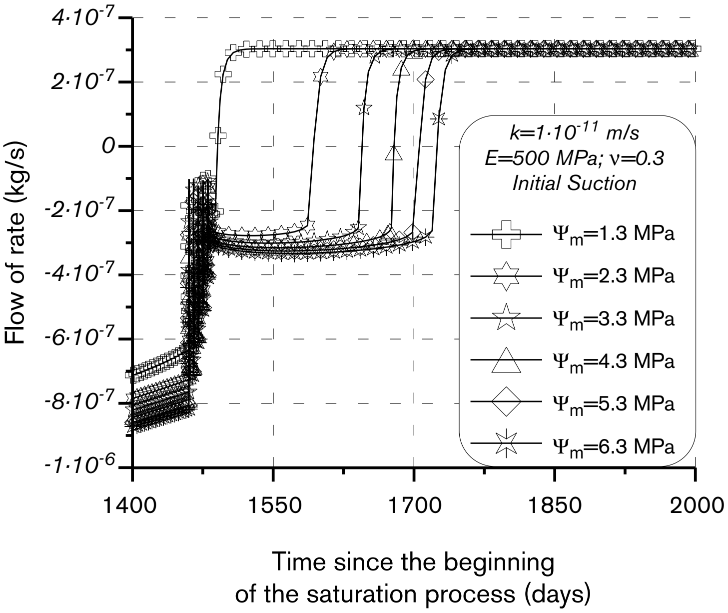


Figure 5-16. *Evolution of water flow rate at mat D4 when performing a global flow test, for different initial matrix suctions when compacting the backfill.*

5.4.2 Prototype Repository

Canister displacement sensors

Six displacement sensors, grouped into one single measuring section, were planned at the bottom of each canister, in deposition holes 3 and 6.

Three of those sensors are placed horizontally on the upper face of the bentonite block, close to the lower lid of the canister and attached to it in a 120° radial array. These sensors will measure potential horizontal displacements of the canister.

The other three sensors are vertically placed in holes drilled in the same bentonite block. These sensors will measure the vertical displacement of the canister, as well as any possible tilt. The points where the sensors are attached to the canister are the same as those of the horizontal sensors.

The displacement sensors are fibre optic based with no electronics inside, but a Thin Film Fizeau Interferometer receives a broadband white light and returns a wavelength modulated light. Hence, it is assured that no electromagnetic interference will affect the readings.

The sensor selected is a rugged version of the FOD 25 from Roctest, manufactured in Incoloy 825 because of the harsh working conditions, assuring water tightness and corrosion resistance. The dimensions of the sensor have been kept as small as possible to minimise perturbations in the system. A recording system is installed on site. One data point per sensor is collected every hour. The mean value per day is stored in a local database.

Supervision and data management is done in a remote way from the main offices of Aitemin in Madrid. The remote control system of Madrid connects via modem periodically with the site for data transmission. A master database is being created with the data gathered and periodic reports, including graphical representation of the evolution of the displacements, will be issued.

Work performed and results obtained

The displacement sensors for deposition hole 3 and the required measurement system were installed in 2001. Due to a malfunction of the heaters in the Canister Retrieval Test the installation work of the Prototype Repository was interrupted. Therefore, during 2002 only the data acquisition for canister 3 tracking monitoring has been done.

Modelling

The modelling work is approached in a stepwise strategy. T and TM analyses are first considered to check the mesh and to compare with analyses performed by other groups. The next step is a THM simulation of one canister, focussing on the behaviour of the bentonite. Finally, at the end of the project, a consideration of the chemical aspects involved in the bentonite buffer will be addressed in a preliminary simulation. UPC performs the modelling with the in-house developed code CODE_BRIGHT.

Work performed and results obtained

During the year 2002 a numerical simulation, of the operational conditions of the test using the code CODE_BRIGHT, has been performed. Particular emphasis has been placed on the analysis of the gaps and the slots that are present after the installation of the canister and the bentonite blocks in the deposition holes. Understanding the role of those gaps and slots in the THM processes might be required for comparing the experimental with the computed data. Among all the simulations performed, quasi-3D geometry and 1D geometry have been found to be the most appropriate when analysing the test. On the one hand, quasi-3D allows incorporating spatial effects limiting the mesh size to reasonable values. On the other hand, 1D geometry involves fewer elements and allows using complex THM models with a reasonable computing time.

Some results from the quasi-3D geometry are presented in this summary. Figure 5-17 shows the basic geometry used in the simulations. A slot between the heater and the bentonite blocks, 1 cm wide and filled with air, has been considered in the analyses. Although in reality this gap will not be regular, since it represents the tolerance between heater and bentonite, the simulation can only reproduce a constant thickness gap. Despite this limitation, the analyses show the main trends in the THM behaviour. The final irregular shape of the slot may introduce eventually some distributions of displacements and stresses, but the main trends are well reproduced by using the regular geometry.

Figure 5-18 and present the radial displacement of the left and right sides of the air gap at different days after the beginning of the experiment. That is, Figure 5-18 shows the movement of the heater boundary whereas Figure 5-19 depicts the horizontal displacement of the bentonite in contact with that gap. Note that due to the expansion of the heater and the bentonite, both boundaries become closer with time. Also, the heater expansion is quite uniform, the expansion of the bentonite is slightly more important on the lower part of the deposition hole. Therefore, that part will be in contact first, although in practice, the process could be dominated by the non-regular nature of the gap and the contact areas may be quite different.

From the interpretation of the numerical simulations of the test carried out during year 2002, some concluding remarks can be drawn:

- The slot between heater and bentonite may be important at the beginning of the experiment, in particular for displacements and stress measurements. Its non-regular nature may lead to difficulties when interpreting field measurements at the beginning of the test.
- According to the model, saturation takes place in around 500 days. This is very sensitive to some parameters that are difficult to specify, i.e. rock permeability. Therefore, this predicted time might vary between deposition holes.
- Temperature in the heater reaches 75°C. Flux value has been changed in the geometry (1D, quasi-3D, etc) in order to reproduce boundary conditions in a realistic way.
- Quasi-3D analyses show a small inhomogeneity in the displacements pattern, i.e. the bottom of the canister undergoes more displacement at the beginning of the process.
- No fundamental differences have been found between the results obtained using different mechanical models. However, the analyses performed using an elasto-plastic model "BBM", which includes irrecoverable deformations, seems to produce more realistic results in terms of displacements.

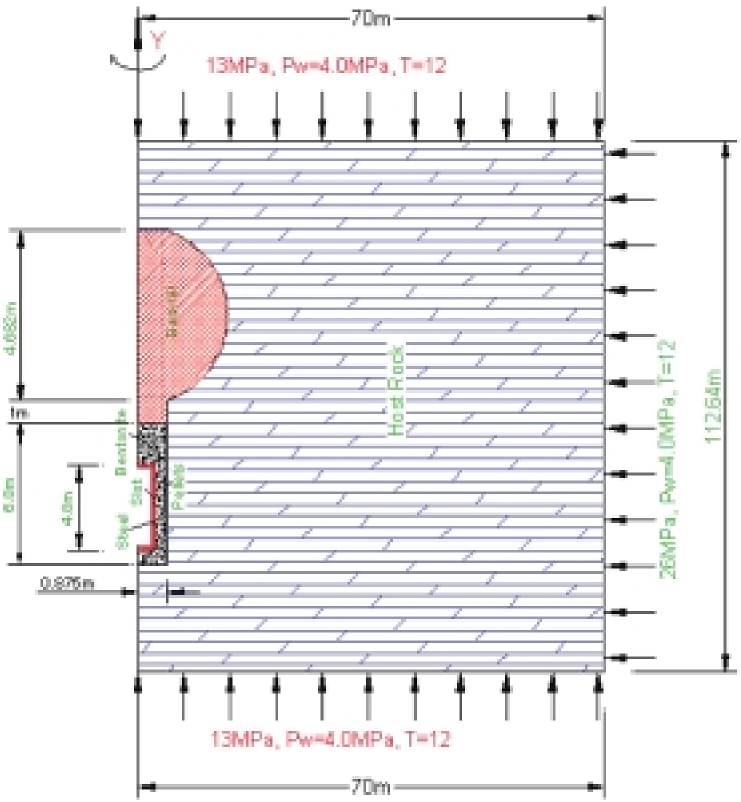


Figure 5-17. *Quasi-3D geometry and boundary conditions used in the simulation of the THM processes of the Prototype experiment.*

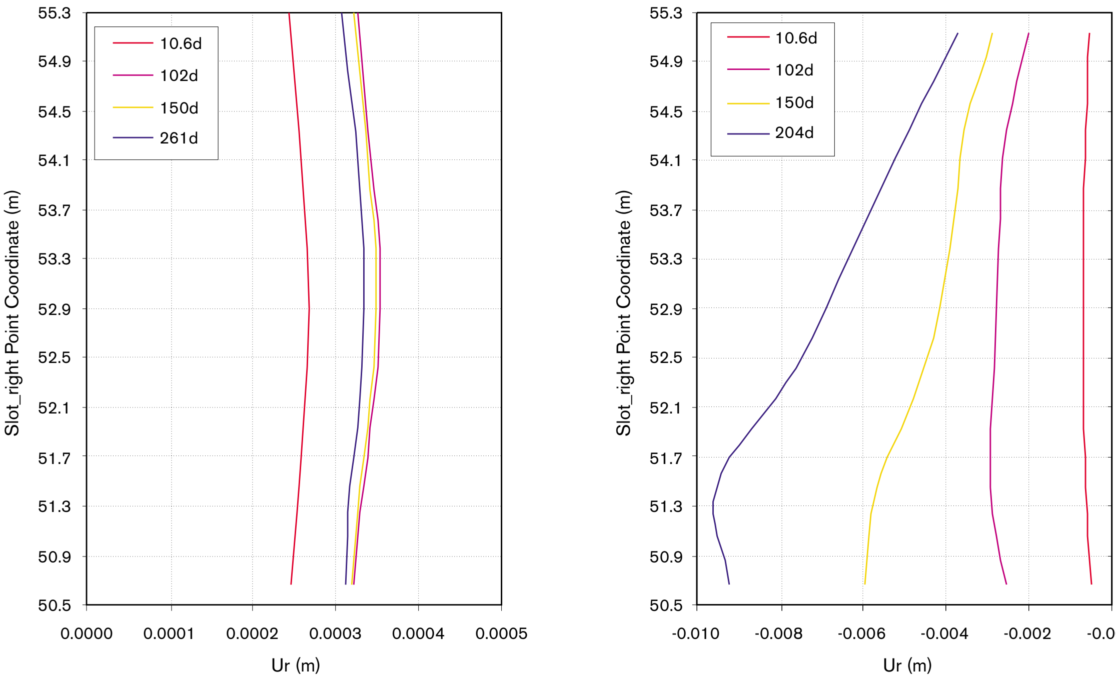


Figure 5-18. *Prototype experiment: Computed radial displacement of the heater.*

Figure 5-19. *Prototype experiment: Computed radial displacements of the bentonite in the boundary close to the heater.*

Supporting laboratory tests

Supporting laboratory tests are also foreseen. CIEMAT is carrying out the following laboratory work suggested by the modelling team:

- Hydraulic conductivity tests on clay compacted at different dry densities and permeated with water of different salinity.
- Determination of retention curves at constant volume, 20 °C, and different dry density and salinity.
- Determination of retention curves at constant volume and 60°C compacted at different dry densities.
- Suction controlled oedometer tests, with suctions up to 40 MPa and vertical loads of up to 9 MPa. The initial dry density and water content of the clay in these tests is that of the blocks manufactured for the *in situ* test.

Work performed and results obtained

The MX-80 clay is being used as sealing material in the Prototype Repository. A more detailed description of this material and of the methodology of the tests performed can be found in the previous Äspö HRL Annual Report /SKB, 2002/.

Hydraulic conductivity

The additional data obtained during 2002 has allowed a better definition of the correlation lines regarding the hydraulic conductivity. All the results are plotted in Figure 5-20, where exponential relations between dry density (ρ_d) and hydraulic conductivity (k) have been drawn for each kind of permeant:

For distilled water: $\log k = -2.94,\ \rho_d = 8.17$

For saline water: $\log k = -2.39,\ \rho_d = 8.78$

The hydraulic conductivity is slightly higher when saline water is used as permeant.

Retention curve at laboratory temperature

The results obtained with the method of the block and the sensor during 2001 have been fitted to the van Genuchten expression (equations 5-1 and 5-2). The parameters found are shown in Table 5-2.

$$\theta_e = \left[\frac{1}{1 + (\alpha h)^{1/(1-m)}} \right]^m \qquad (5\text{-}1)$$

$$\theta_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (5\text{-}2)$$

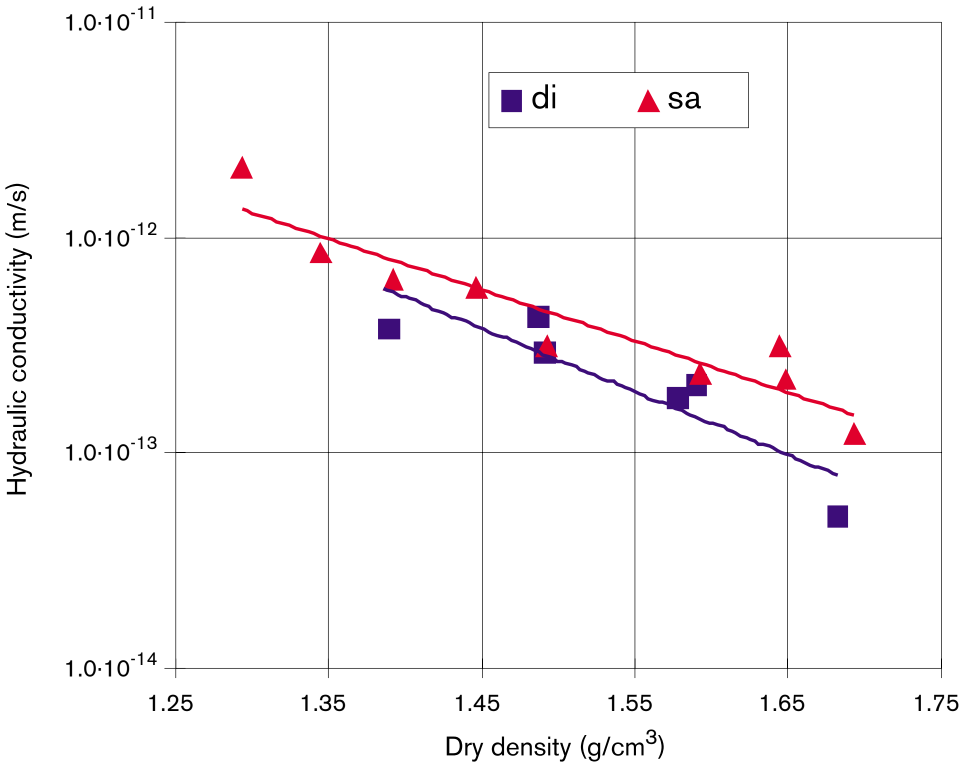


Figure 5-20. *Results of the hydraulic conductivity tests with compacted MX-80 (di = distilled, sa = saline water).*

Table 5-2. Parameters of the van Genuchten expression fitted to the retention curves for MX-80 clay.

Dry density (g/cm³)	Kind of water	α	θ_s	n[1]
1.50	Distilled	0.0004	0.51	1.79
	Saline	0.0003	0.50	1.97
1.60	Distilled	0.0003	0.47	2.00
	Saline	0.0004	0.51	1.88
1.70	Distilled	0.0002	0.48	2.08
	Saline	0.0002	0.48	2.15
1.80	Distilled	0.0003	0.56	2.04
	Saline	0.0002	0.54	2.20

[1] n=1/(1–m)

In order to check the performance of this methodology (the method of the block and the sensor), a retention curve at 20°C is being determined in non-deformable cells /Villar et al, 2001/. A wetting/drying path for a dry density of 1.60 g/cm^3 and an initial water content of 9% (the hygroscopic one, approximate suction 110 MPa) is being performed in a non-deformable cell. The results obtained are shown in Figure 5-21. A good correlation is observed between both methods. The advantage of the block and sensor method, fine tuned for the Prototype Repository project, is that it is easier and faster to perform.

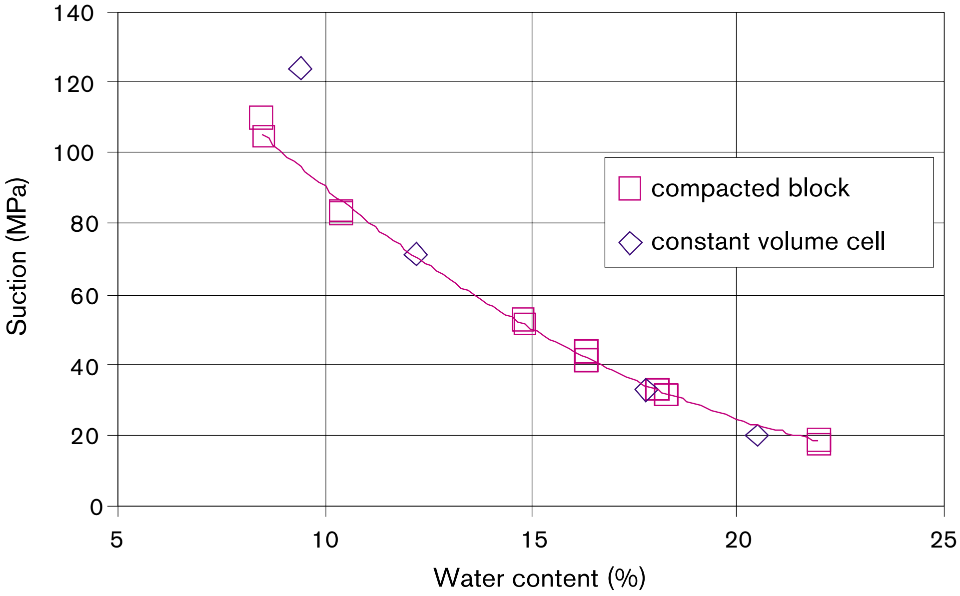


Figure 5-21. *Retention curves at 20°C determined with two different methods for MX-80 clay compacted at dry density 1.60 g/cm^3.*

Retention curve at 60°C

The determination of the retention curves at 60°C started in December 2001. The paths followed have been chosen taking into account the possible evolution of the clay in the barrier:

- Wetting paths for dry densities 1.79 and 1.60 g/cm^3, from initial water content of 17% (approximate suction 40 MPa).
- Drying/wetting paths for dry densities 1.79 and 1.60 g/cm^3, from initial water content of 17% (approximate suction 40 MPa).
- Wetting paths for dry density 1.30 g/cm^3, from an initial water content of 9% (the hygroscopic one, approximate suction 110 MPa).

The retention curves at 60°C are being determined in non-deformable cylindrical cells designed to prevent variations in the volume of the sample. The cell is placed in a desiccator with a sulphuric acid solution. The suction control method is, therefore, through the control of relative humidity. For determination of the retention curves at 60°C, the desiccator is placed inside an oven with regulated temperature. The results obtained up to now are shown in Figure 5-22.

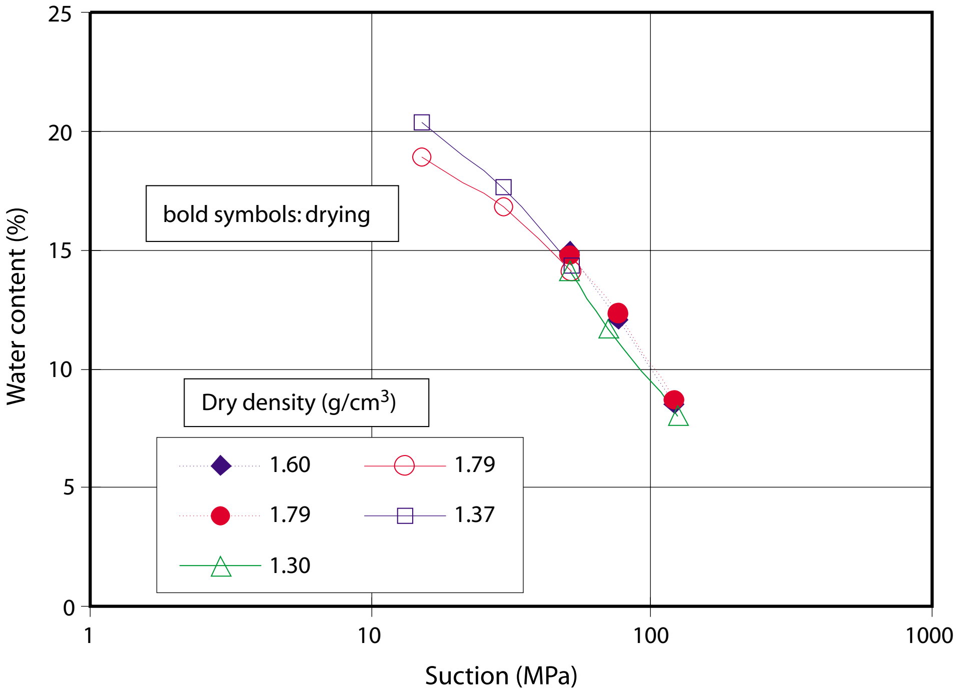


Figure 5-22. *Retention curves for MX-80 clay at constant volume and at 60°C.*

Suction controlled oedometer tests

The suction controlled oedometer tests proposed include suctions up to 40 MPa and vertical loads of up to 9 MPa. The samples have been hydrated under a low vertical load and, once saturated, they have been loaded. The initial dry density and water content of the clay in these tests are the same as those of the blocks manufactured for the *in situ* test: dry density 1.79 and 1.69 g/cm^3 and water content 17%.

Two techniques have been used to control suction: axis translation and the imposition of relative humidity. In both cases, suction is applied but not measured. The axis translation technique allows the control only of matrix suction, while the control of the relative humidity modifies the total suction. Specifically, suction has been applied by nitrogen pressure, for values ranging from 0.1 and 14 MPa, and by solutions of sulphuric acid for values between 3 and 500 MPa. The tests are being performed at a constant temperature of 20°C.

The time required for stabilisation of every suction-step is very long, more than 60 days. As a consequence the duration of each test is very long. Only one of the tests performed in the nitrogen cells has been finished.

The results obtained in the oedometer tests (four) performed are shown in Figure 5-23. A good agreement is found between the two methods of suction control, what, as in the case of the retention curves, would be an indication of the lack of influence of the osmotic suction in the behaviour of the clay. The high swelling developed for the lower suctions attenuates the initial difference in void ratio of the specimens.

On the other hand, the oedometric curves of the loading paths after hydration (Figure 5-24) show clearly the decrease in the apparent preconsolidation pressure to values bellow 1 MPa, which is due to the previous saturation under a low vertical load.

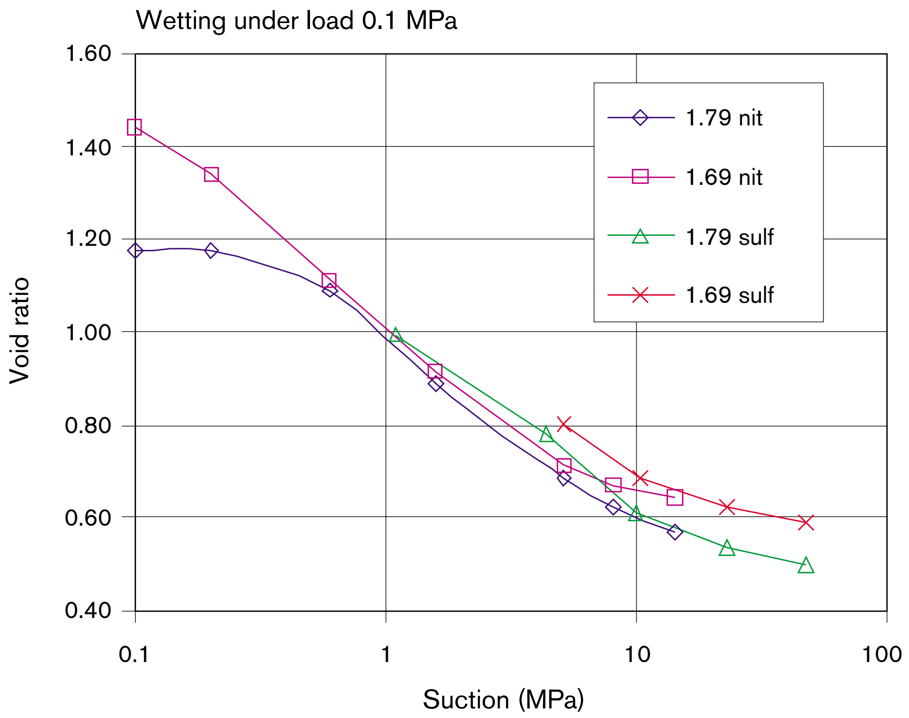


Figure 5-23. Void ratio evolution as a function of suction in the oedometric tests. MX-80 clay compacted to two densities (expressed in g/cm^3). Suction control by nitrogen pressure(nit), suction control by solutions (sulf).

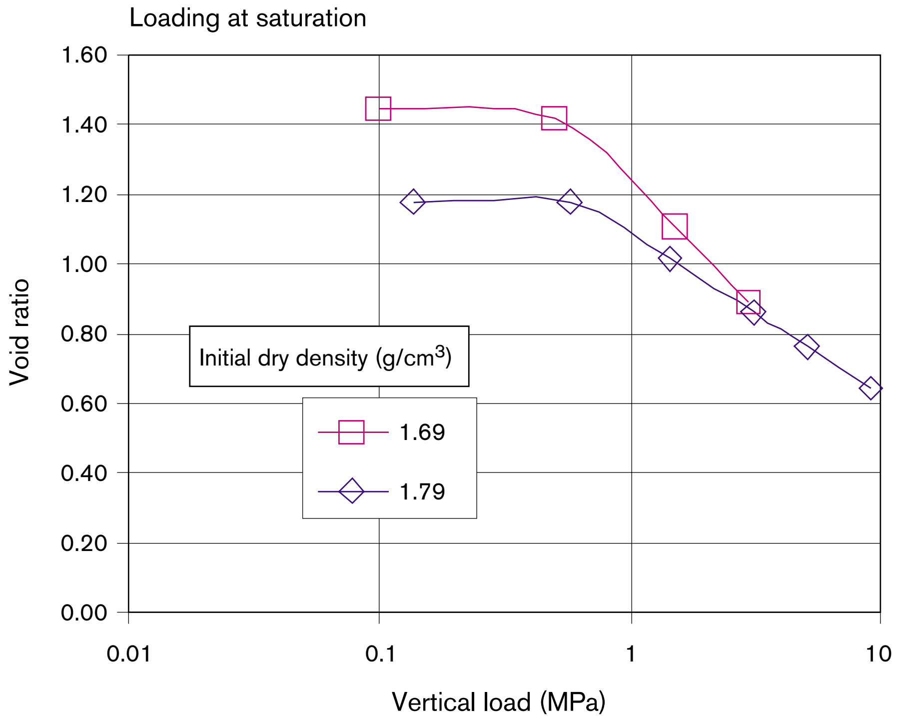


Figure 5-24. Oedometric curves of the tests carried out with control of suction by nitrogen pressure (loading paths).

5.5 JNC

Japan Nuclear Cycle Development Institute (JNC) actively participated in the Äspö Task Force on Modelling of Groundwater Flow and Transport of solutes and in the TRUE Block Scale Continuation project during 2002. The primary activity within the Task Force has been single fracture tracer transport simulations under experimental and safety assessment boundary conditions for Task 6, "Performance Assessment Modelling Using Site Characterisation Data".

During 2002, JNC activities for the TRUE Block Scale Continuation project focused on project reporting. Reports were prepared describing development and testing of the hydrostructural models, channel network (CN) transport modelling, and testing of hypotheses regarding solute transport processes. In addition analyses were carried out to study compartmentalisation and transport pathways within the TRUE Block Scale rock mass.

5.5.1 Task Force on Modelling of Groundwater Flow and Transport of solutes, Task 6

During 2002, JNC participated in sub-tasks 6A and 6B, which compared performance assessment (PA) and experimental time scale simulations along a pipe transport pathway. JNC also participated in sub-task 6B2, carrying out single fracture transport simulations on a wide variety of generic heterogeneous 2D fractures using both experimental and safety assessment boundary conditions. The heterogeneous 2D fractures were implemented according to a variety of heterogeneity patterns in the plane. Multiple immobile zones were considered including stagnant zones, infillings, altered rock walls, and intact rock.

The objective of JNC/Golder activities on Task 6 during 2002 was to improve the understanding of the implications of using 1D rather than 2D modelling for solute transport in single fractures. 1D transport approaches ignore multiple pathways, complex head field, and variability in immobile zones which occur in plane. Although the 1D approach is clearly a significant simplification, it is used almost universally in PA. JNC efforts focused on understanding the effect of different 2D fracture assumptions, with particular focus on the representation of the spatial structure of fracture infillings.

The extent to which the 1D and 2D approaches differ depends on the spatial pattern and distribution of immobile zone properties in the fracture plane. The JNC/Golder team therefore implemented a series of alternative spatial patterns:

- Channelled aperture pattern, wide channels.
- Channelled aperture pattern, narrow channels.
- Homogeneous (unchannelled) with wide pattern.
- Homogeneous (unchannelled) with narrow pattern.

An example of these patterns is shown in Figure 5-25. For each of these patterns, multiple realisations were implemented as stochastic continuum fields. JNC/Golder believes that, at least for experimental time scales, fracture infillings and coatings may dominate transport behaviour. As a result, it is not necessarily the pattern of aperture on a fracture plane which is important, but rather the pattern of infillings. Based on observations at Äspö and at JNC's facilities in Kamaishi and Mizunami, JNC has developed a

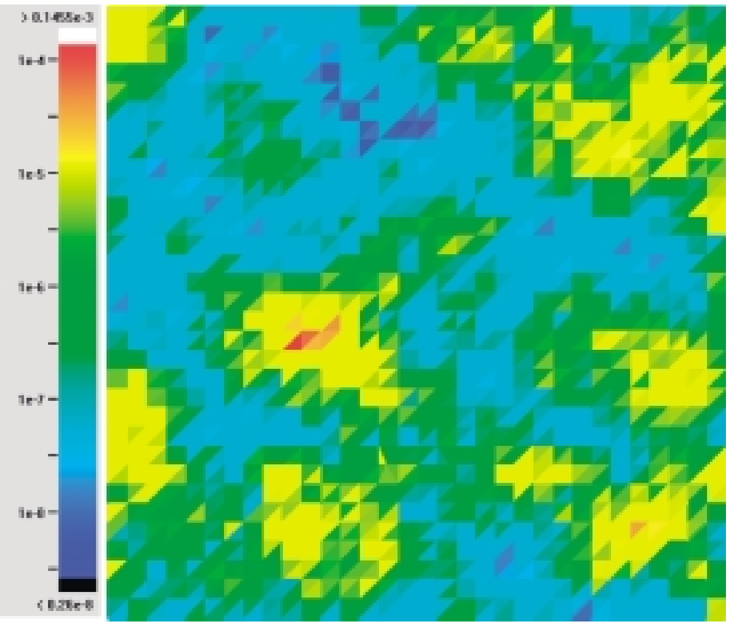


***Figure 5-25.** Variability of transmissivity on fracture surfaces.*

conceptual model in which small flow apertures correspond to locations with significant infill, and large flow apertures correspond to the areas with lower amounts of infilling materials. Thus, the primary driver of in plane heterogeneity at the 5 to 10 m experimental transport scale is the spatial pattern of infillings. This assumed correlation between flow aperture (represented by transmissivity) and immobile zone thickness is given in Figure 5-26.

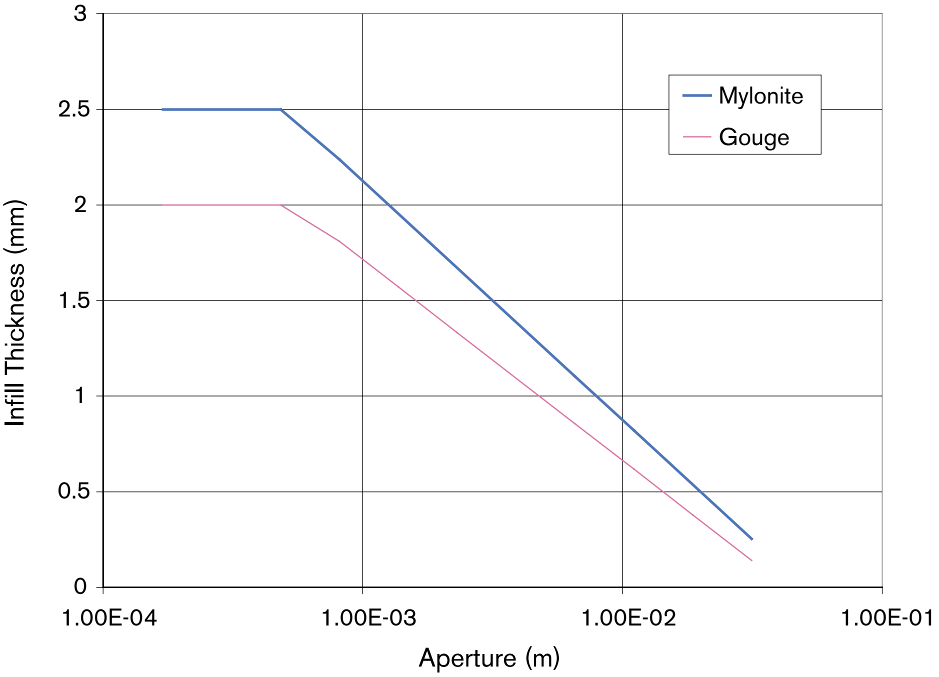


***Figure 5-26.** Correlation between flow aperture (represented by tansmissivity) and immobile zone thickness (infill thickness).*

For each of the assumed spatial patterns of flow aperture (transmissivity) and immobile zone properties, immobile zone solute transport properties were conditioned to the observed breakthrough of the STT-1b tracer experiment. These conditioned models were then used for PA time scale transport over a 15 m transport distance.

Results

As expected, it was possible to calibrate all of the disparate spatial fields to the observed STT-1b breakthrough by varying the correlation between transmissivity and transport aperture, and the correlation between transmissivity and immobile zone thicknesses. An example calibrated breakthrough curve is provided in Figure 5-27. This illustrates the observation that the details of the in-plane fracture properties are very difficult to constrain on the basis of breakthrough curves.

The primary issue to be resolved, however, is whether different conditioned 2D fracture models produce significantly different PA time scale transport results. Figure 5-28 illustrates the distribution of heads for a PA boundary condition assuming a gradient of 0.1%. The head fields are somewhat different, and do indicate some differences in channelling. However, the difference is not large enough to indicate a need for 2D rather than 1D PA modelling. Tracer breakthrough under PA boundary conditions was calculated for iodine, strontium, cobalt, technetium, and americium. In general, the different 2D fields produced PA scale breakthrough curves offset by up to approximately one order of magnitude in time (Figure 5-29).

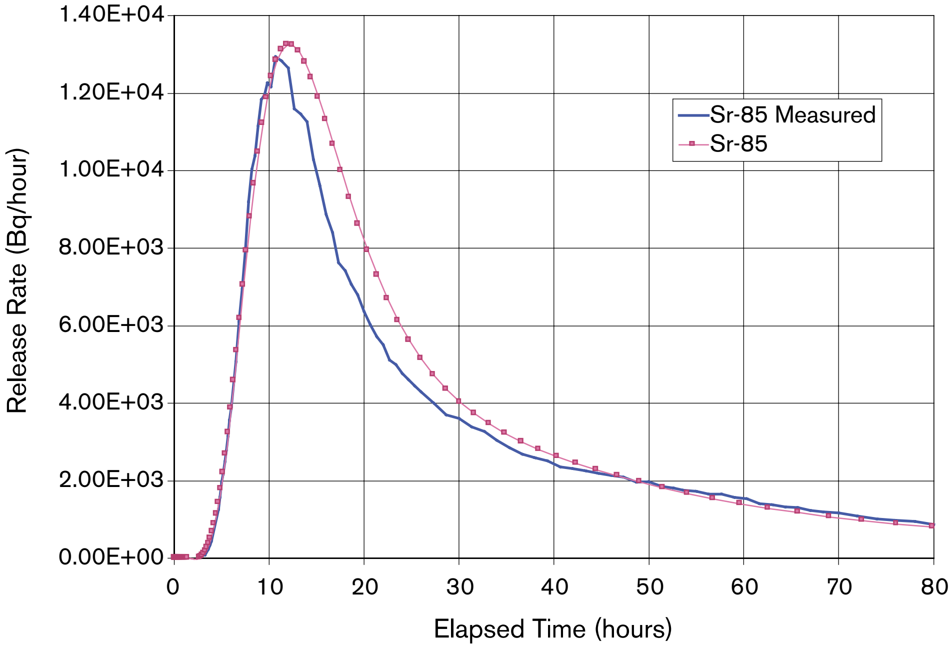


Figure 5-27. *Conditioned STT-1b experimental breakthrough, ^{85}Sr (stochastic field #3).*

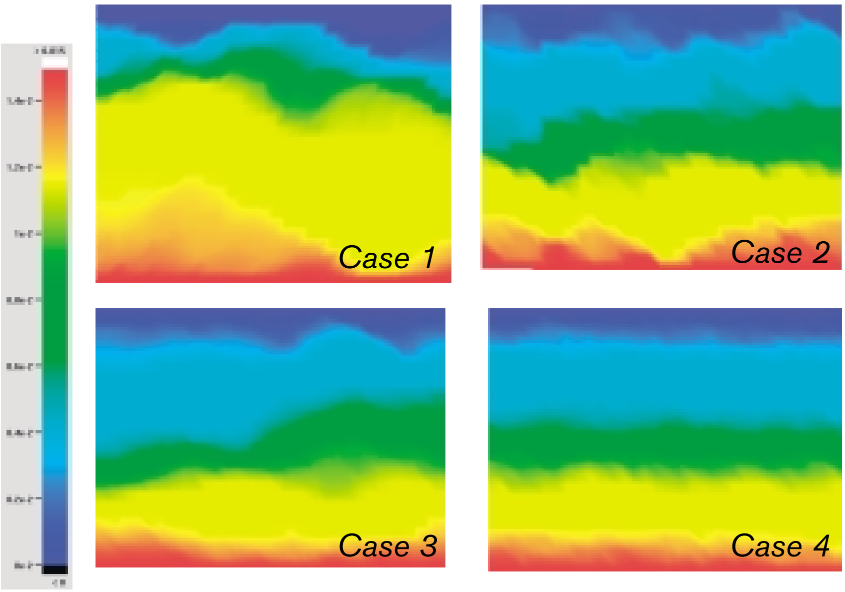


Figure 5-28. Head distributions for PA boundary condition.

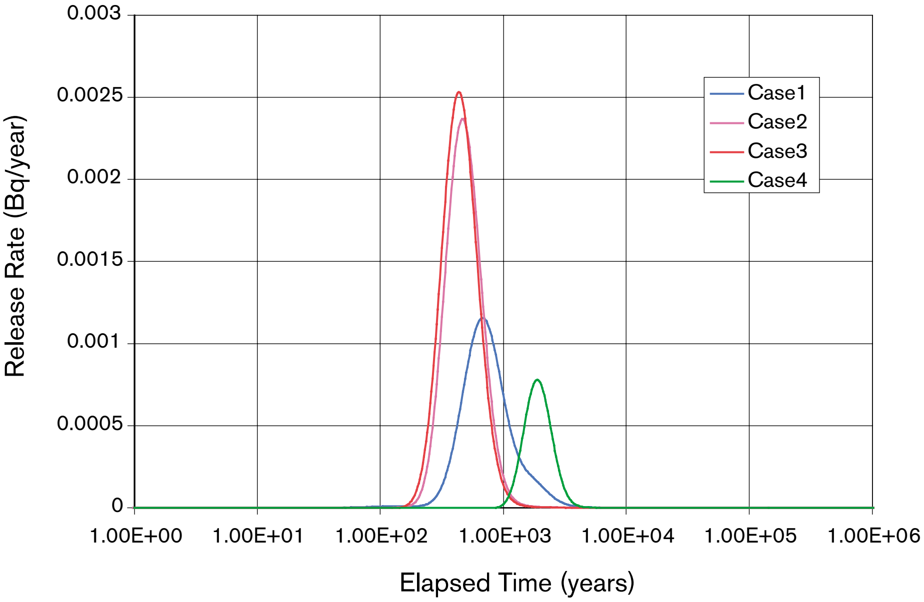


Figure 5-29. Variability in PA time scale breakthrough between stochastic fields, cobalt.

5.5.2 TRUE Block Scale

JNC has participated in the Äspö TRUE Block Scale project since 1998. In this project, SKB and its partners are characterising 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. Efforts during 2002 concentrated on analysis of experimental results and reporting of simulations and analyses.

JNC's objective within the TRUE Block Scale project during 2002 was to advance the understanding of the nature of flow and transport in fracture networks at 50 to 100 m scales.

During 2002, the JNC/Golder team evaluated two of the fundamental hydrostructural model assumptions of the TRUE Block Scale team: (a) that the transport experiments are carried out in single essentially planar fractures, or networks of linearly connected planar fractures, and (b) that retention in the TRUE Block Scale rock mass is controlled by microstructure (within fracture planes) rather than fracture network effects.

Results

JNC carried out flow dimension analysis to evaluate the transport pathway geometry imbedding in the hydrostructural model. JNC/Golder analysed short-term build-up in boreholes KI0025F02 and KI0025F03, and the flow portions of Phase A, PT-1, and PT-3 tracer tests. Figure 5-30 shows an example analysis of flow dimension from transient hydraulic data. Table 5-3 summarises flow dimensions obtained from the analysis. The flow dimensions from these experiments are generally one to two, which is consistent with transport in planar fractures. If the transport pathways involved significant fracture network effects, dimensions higher than two would be expected.

TRUE Block Scale modelling through 2001 relied upon a calibrated enhanced retention (K_d) to explain observed solute retention. The need for a calibrated K_d indicates a lack of understanding of fundamental retention processes. During 2002, SKB developed an updated microstructural model for fractures in the TRUE Block Scale rock for Task 6C /Dershowitz et al, 2003/. This model includes significant immobile zone porosities of

Table 5-3. Dimensions (n) obtained from flow dimension analysis. (The value r is the distance between the measured response in the numbered structure and the test source, T is the transmissivity).

Structure #	Borehole: KI0025F03			Borehole: KI0025F02		
	n	T (m^2/s)	r (m)	n	T (m^2/s)	r (m)
7				3	$1.0\cdot10^{-6}$	
6				1	$1.0\cdot10^{-7}$	27
23	1.3	$1.0\cdot10^{-8}$	85	1	$5.0\cdot10^{-9}$	27
22	2	$7.0\cdot10^{-9}$	17	2	$2.0\cdot10^{-7}$	208
20	1.3	$1.0\cdot10^{-6}$	85	2	$4.0\cdot10^{-7}$	
13	2	$4.0\cdot10^{-8}$	85	1	$1.5\cdot10^{-7}$	208
P3-Splay	2	$4.0\cdot10^{-9}$	17	1	$1.0\cdot10^{-8}$	
19				2	$2.0\cdot10^{-6}$	
10				2.5	$1.0\cdot10^{-7}$	

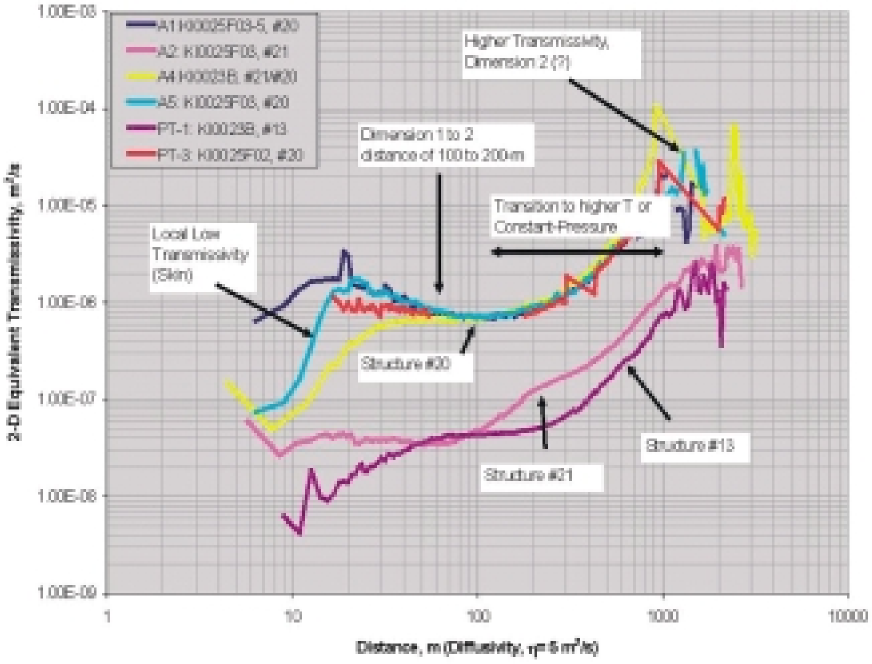


Figure 5-30. Transmissivity-distance for Phase A and PT hydraulic transient results.

cataclasite, fracture coating, gouge, and breccia. JNC/Golder used this updated microstructural model to simulate TRUE Block Scale tracer tests. Direct apply of the updated microstructural model produces more retention than observed *in situ*, which is the opposite of the result obtained when using K_d values determined in the laboratory for intact rock (Figure 5-31). This result, although preliminary, indicates that improved characterisation and understanding of fracture microstructures are the keys to the comprehension of solute retention processes in fracture networks.

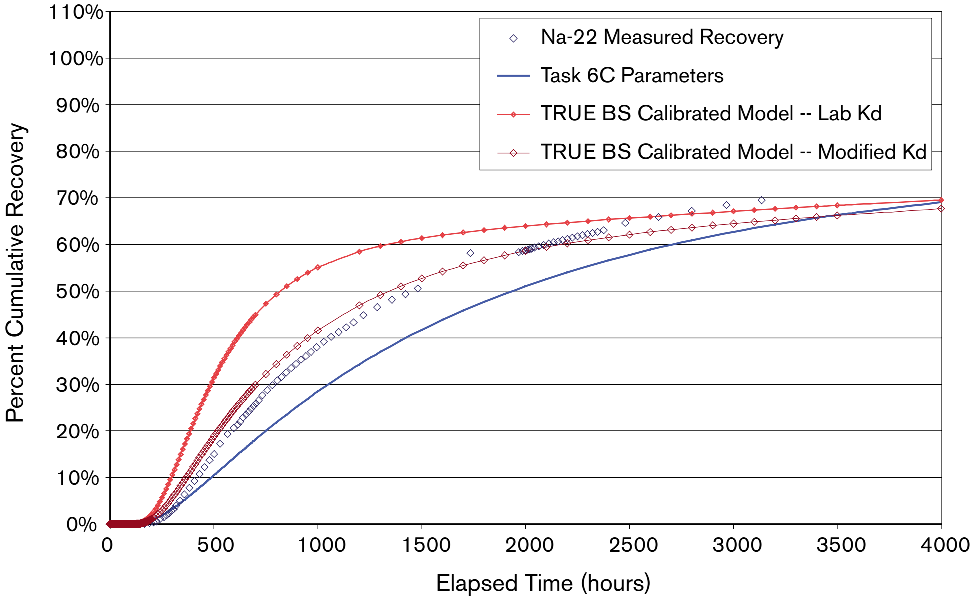


Figure 5-31. Effect of updated micro-structural model on solute retention (C-3 sorbing tracer experiment).

5.5.3 Prototype Repository

JNC participated in the Prototype Repository project since 2000. JNC participated in Work Packages of THM modelling of buffer, backfill and interaction with near-field rock, as well as C modelling of buffer, backfill, and groundwater.

THM modelling of buffer, backfill and interaction with near-field rock (WP)

JNC has validated the coupled THM analysis numerical code "THAMES". THAMES was originally developed by Professor Ohnishi, Kyoto University /Ohnishi et al, 1985/. Hazama Corporation and Kyoto University validated the code for JNC. THAMES was applied to the simulation of the coupled THM phenomena in and around the engineered barrier system (EBS). The work was documented in the second progress report on research and development for the geological disposal of the HLW in Japan /JNC, 2000/.

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

Results

In the last Äspö HRL Annual Report /SKB, 2002/, JNC described the results from the two dimensional analysis of the Prototype Repository named prediction analysis A /Sugita et al, 2002/. In this report, the analytical results of the prediction analysis B (three dimensional analyses) are summarised.

JNC has prepared a three-dimensional analyses of the Prototype Repository and all parameter for the coupled THM analytical code THAMES were published last year /Sugita et al, 2002/. The analyses were carried out using a 3D model. Figure 5-32 and Figure 5-33 show the model geometries. Figure 5-32 is a "one-heater model" and Figure 5-33 is a "two-heater model". The analysis region of one-heater model is 3 m in the y- direction (along the test drift), 5 m in x-direction, and 60 m in height. The analysis region of two-heater model is 12 m in y-direction (along the test drift), 5 m in x-direction, and 60 m in height. The applicability of THAMES code to MX-80 bentonite buffer was investigated by using the one-heater model whereas the effect of a series of deposition holes was tested with the two-heater model.

The used initial conditions and boundary conditions are given in Table 5-4 and shown in Figure 5-34.

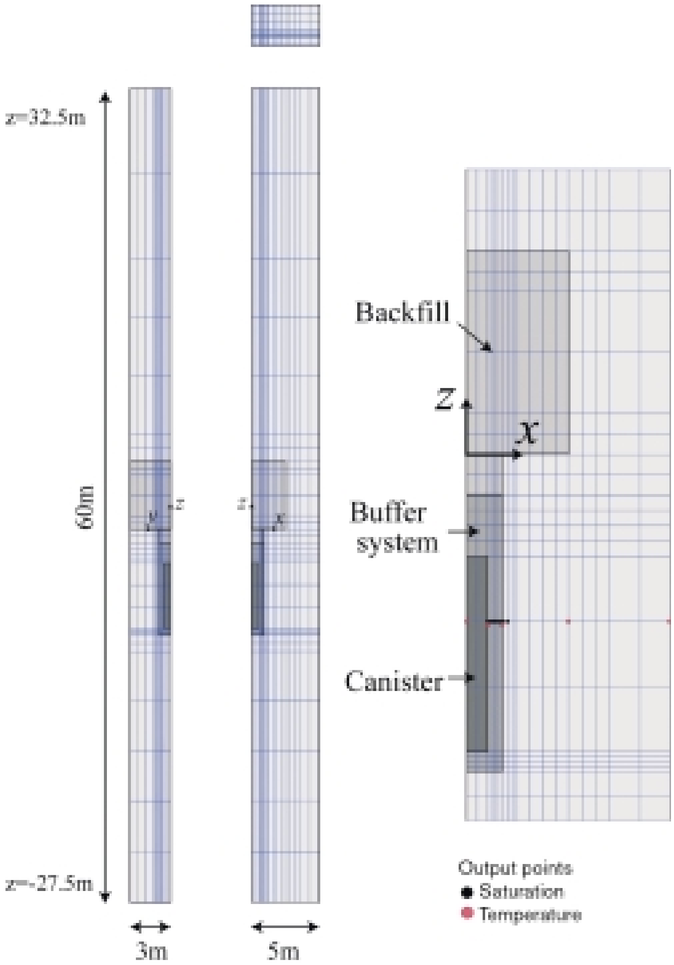


Figure 5-32. *Model geometry, one-heater model.*

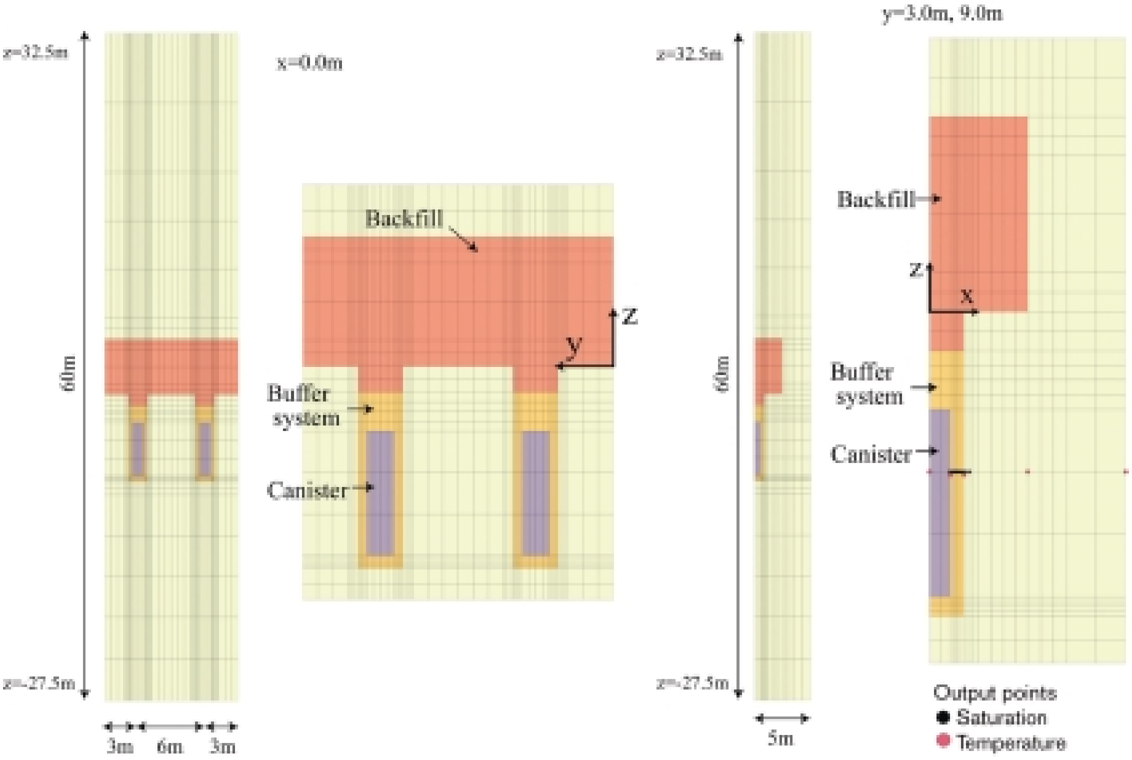


Figure 5-33. *Model geometry, two-heater model.*

Table 5-4. Initial and boundary conditions used in the one-heater model and in the two-heater model.

Initial and boundary conditions	One-heater model	Two-heater model
Initial conditions		
Water head, surrounding rock	400 m	400 m
Degree of saturation, buffer	60%	60%
Degree of saturation, backfill	60%	60%
Temperature	20°C	20°C
Boundary conditions		
Hydraulic conditions		
Upper surface and bottom	constant	constant
y=12 m and x=5 m	–	constant at initial value
Other surfaces	no flow	no flow
Thermal conditions		
Upper surface and bottom	constant	constant
y=0 m and x=5 m	–	constant at initial value
Other surfaces	adiabatic	adiabatic
Mechanical conditions	normal direction (fixed)	normal direction (fixed)
Heater flux (W)	1800 (constant)	1800 (constant)

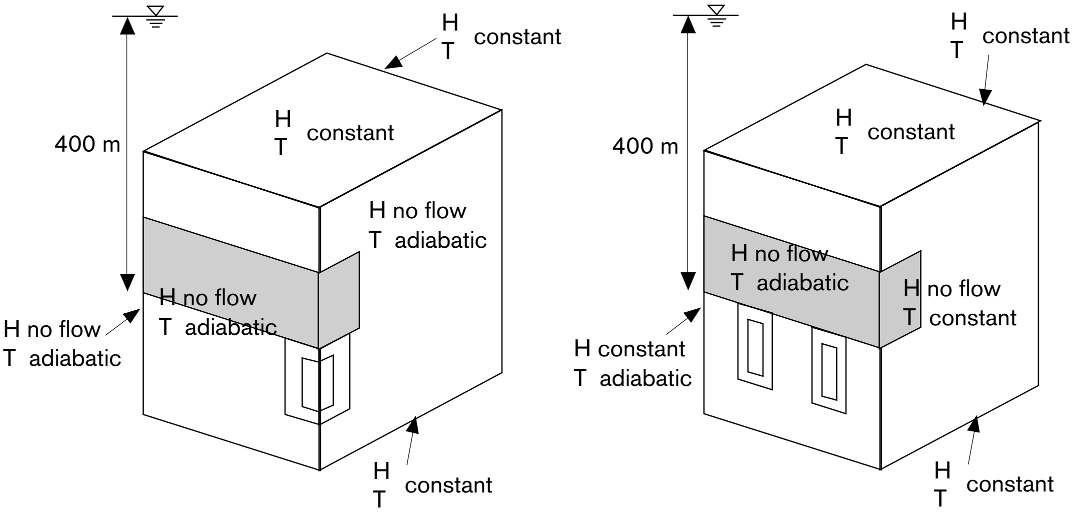
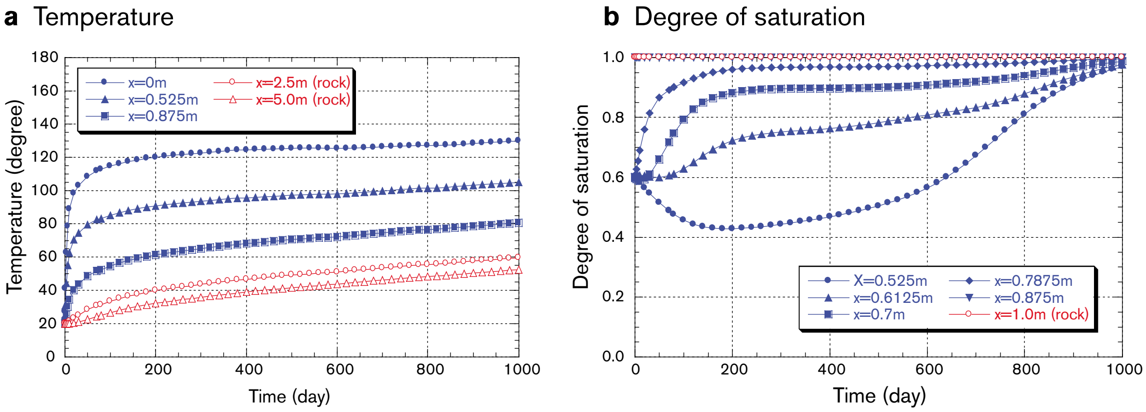


Figure 5-34. Boundary conditions, one-heater model and two-heater model.

Figure 5-35 shows results from the simulation with the one-heater model. Figure 5-35a shows the time history of temperature at the output points. The output points are along the line y=0 m and z=–3.1 m as shown in Figure 5-32. Temperature increases after 1000 days because the output power of heater is constant. Figure 5-35b shows the time history of degree of saturation in the buffer and the rock mass. The degree of saturation close to the heater decreases until 200 days after the start of heating and the minimum value is about 0.4. After that, the saturation in the buffer close to the heater increases and becomes almost fully saturated after 1000 days from the start of heating. The degree of saturation in the buffer, close to the rock mass, increases from the start of heating. This is due to the infiltration of groundwater from the rock. Figure 5-35c shows the time history of stress in the buffer close to the heater and close to the rock mass. Both stresses increase due to the swelling of the buffer. Stress in the buffer close to the rock mass is larger than the stress close to the heater and it became about 6.5 MPa after 1000 days from the start of heating. Figure 5-36 shows the distribution of temperature around the EBS and distribution of the degree of saturation in the buffer after 200 days.



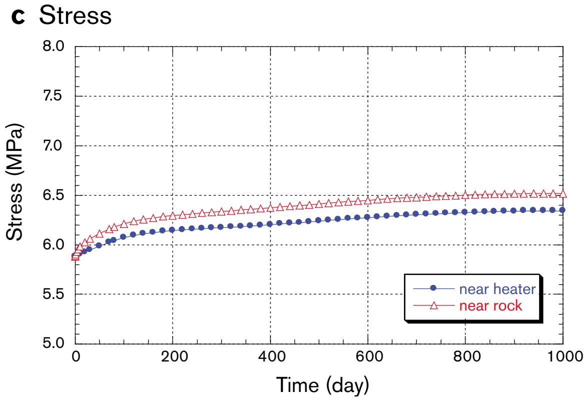


Figure 5-35. *Simulation results by one-heater model.*

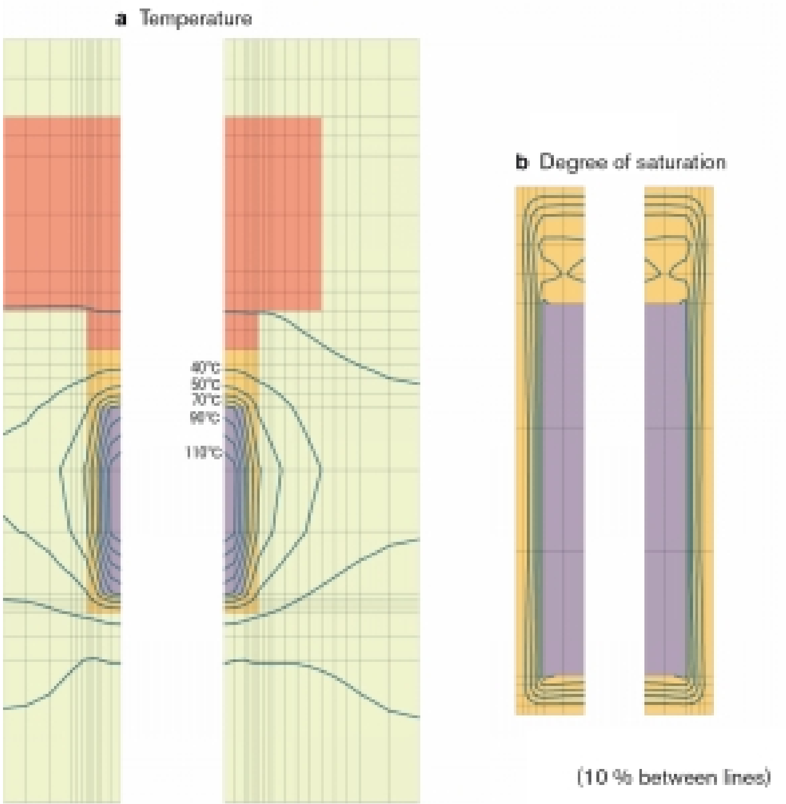


Figure 5-36. *Temperature and saturation after 200 days, one-heater model.*

Figure 5-37 shows results in the form of the time history of the temperature at the output points for the simulation with the two-heater model. Figure 5-37a shows temperature evolution along the line y=3 m and z=–3.1 m and Figure 5-37b shows the temperature along the line y=9 m and z=–3.1 m. The temperature is lower in this simulation compared to the simulation with the one-heater model. This can be explained by the fact that the temperature is constant at the boundary x=5 m. Furthermore, the temperature decreases gradually after the peak value. The temperature distribution around the two deposition holes differs, because the temperature at the boundary y=12 m is constant. Figure 5-38 shows the time history of the degree of saturation in both deposition holes. The temperature difference between the two holes is very small. Figure 5-39 shows the temperature distribution in the plane x=0 m. Differences in the temperature distributions around the two deposition holes can be explained by the applied boundary conditions. The model surface on the right side has an adiabatic temperature boundary condition and the surface on the left side has a constant temperature boundary condition.

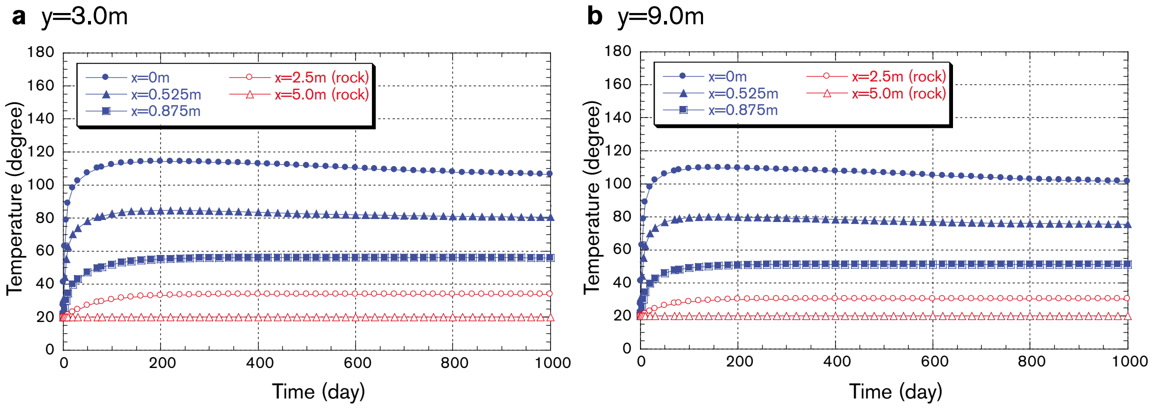


Figure 5-37. Time history of temperature in buffer and rock mass, two-heater model.

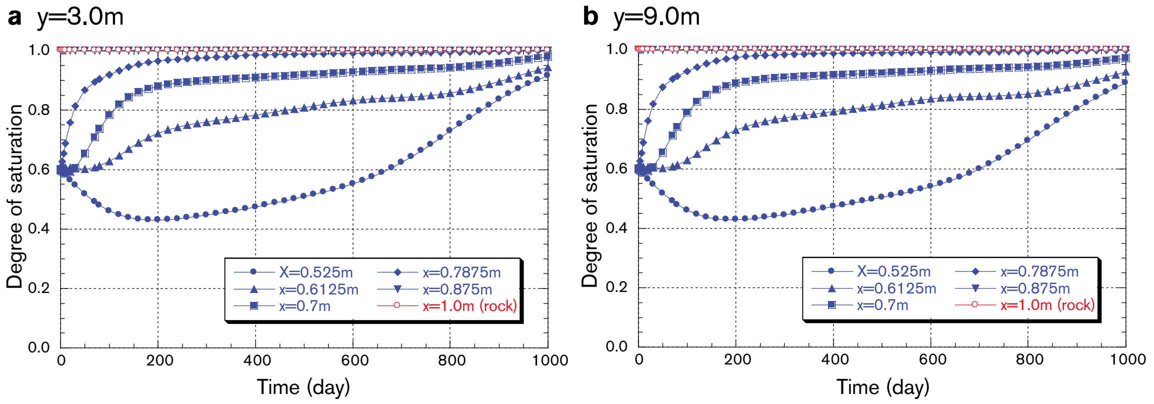


Figure 5-38. Time history of saturation in buffer and rock mass, two-heater model.

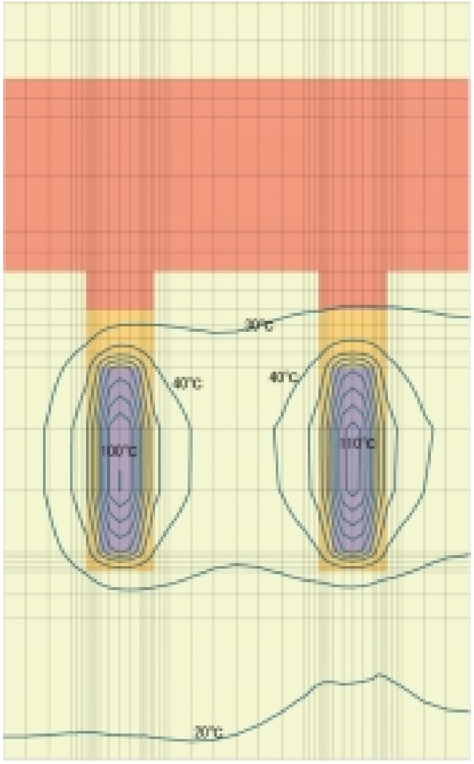


Figure 5-39. Temperature after 200 days, two-heater model.

Figure 5-40 and Figure 5-41 show the temperature and saturation evolution in the buffer in the two different models. The temperature in the one-heater model is higher than that in two-heater model. This is an effect of the applied boundary conditions. In the one-heater model, all vertical boundary surfaces have adiabatic temperature boundary conditions, whereas, these surfaces have constant temperature boundary conditions in the two-heater model. In the two-heater model, the temperature around the heater at y=9 m (left heater Figure 5-39) was lower than that around the heater at y=3 m (right heater in Figure 5-39). The reason is that the left side of the model has constant temperature boundary conditions. The re-saturation time, in one-heater model, was shorter than in the two-heater model. The reason is that the diffusivity of water in bentonite is higher at higher temperatures and the temperature in the one-heater model is higher than the temperature in the two-heater model. The time for saturation of buffer in the left deposition hole in Figure 5-39 (y=9 m) was shorter than that in the right deposition hole (y=3m). This is also an effect of the temperature.

From these simulation results, it was concluded that the temperature distribution around a deposition hole is highly dependent on the applied boundary conditions. Especially, the time for re-saturation is dependent on the temperature distribution. Therefore, it is important to accurately select the boundary condition for the simulations. Seepage in the buffer from the rock mass is dependent on the permeability of the rock mass and the pore pressure distribution in the rock mass. It is important to understand these characteristics in order to evaluate the saturation phenomena in the buffer.

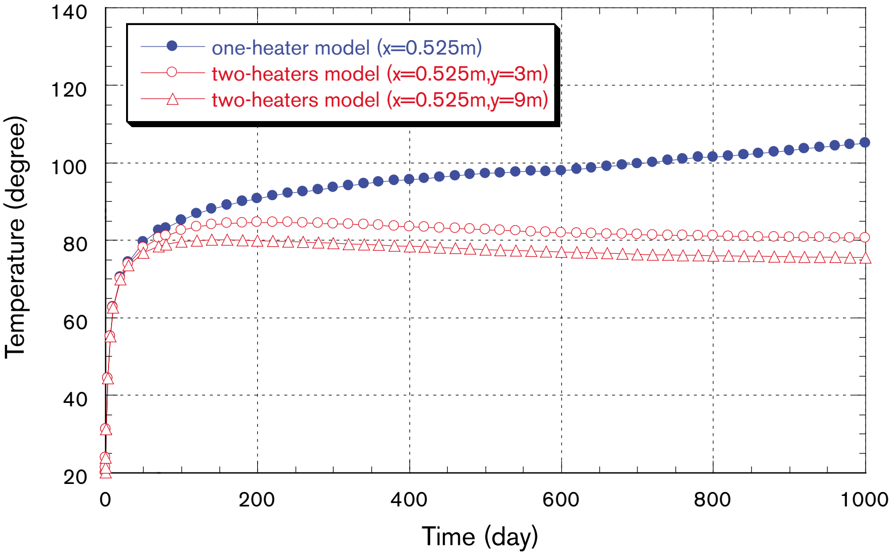


Figure 5-40. *Comparison of temperature in the different models.*

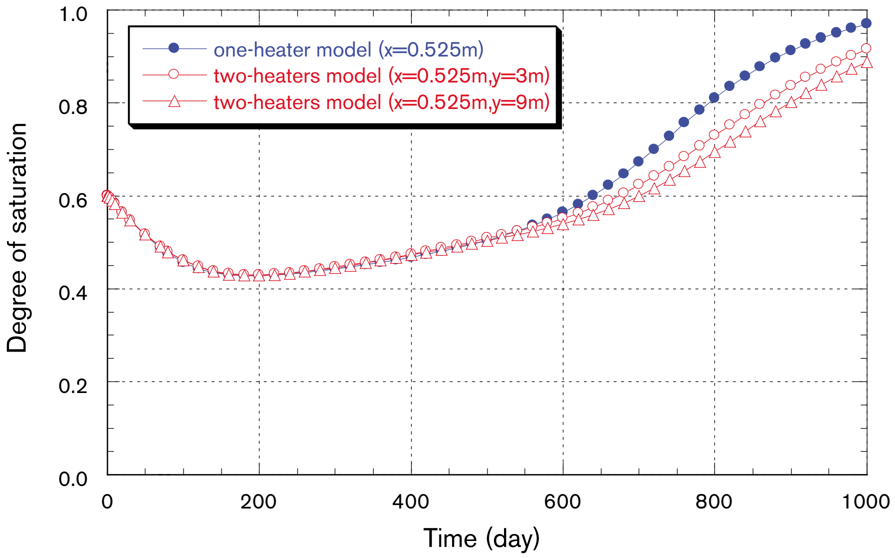


Figure 5-41. *Comparison of degree of saturation in the different models.*

C modelling of buffer, backfill, and groundwater (WP)

Chemical processes are significant processes in the over-pack containments and the radionuclide migration performance assessment (PA). JNC considers that the THM analysis has to be developed to a THMC analysis. However, chemical processes are not simple. The significant chemical processes to be considered have to be selected. JNC also needs the database for the selected chemical processes. Therefore, JNC started the studies of coupling of the C and THM processes in the modelling in 2001. This is done to clarify the chemical evolution of the near-field for performance assessment in HLW.

Results

In the last annual report /SKB, 2002/, JNC described the concept of development of the THMC model. JNC has developed a primitive (prototype) THMC code, which realises one-way coupling from coupled THM processes to mass transport with simple chemical processes (see Figure 5-42).

For advanced coupled THMC simulations, a platform has been constructed, which can control each code and common data. The performance of the platform has been tested against coupled simulations of mass transport and geochemistry.

This year JNC has started to extend the primitive (prototype) THMC code to realise fully coupling among THM processes, mass transport and geochemical processes.

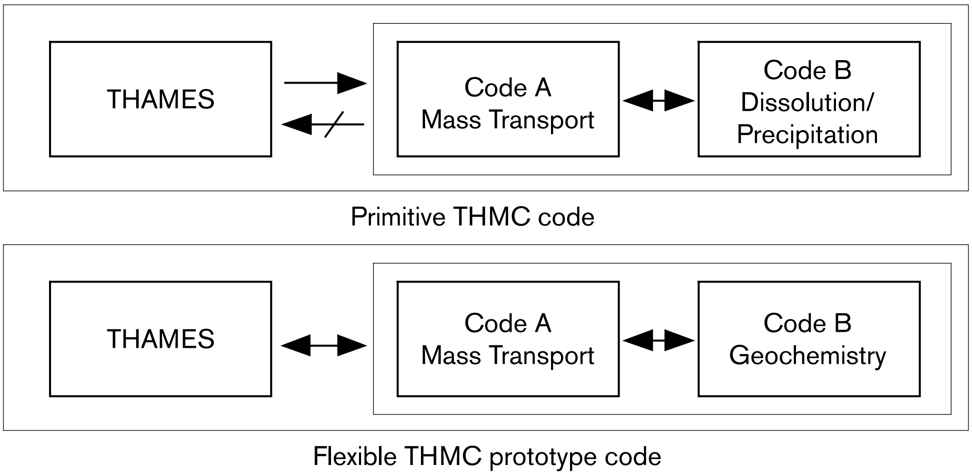


Figure 5-42. *Concept of the THMC numerical code.*

5.6 CRIEPI

CRIEPI joined the Äspö HRL project together with JNC and participate mainly in tasks of demonstrating modelling and analytical methods for groundwater flow and radionuclide migration.

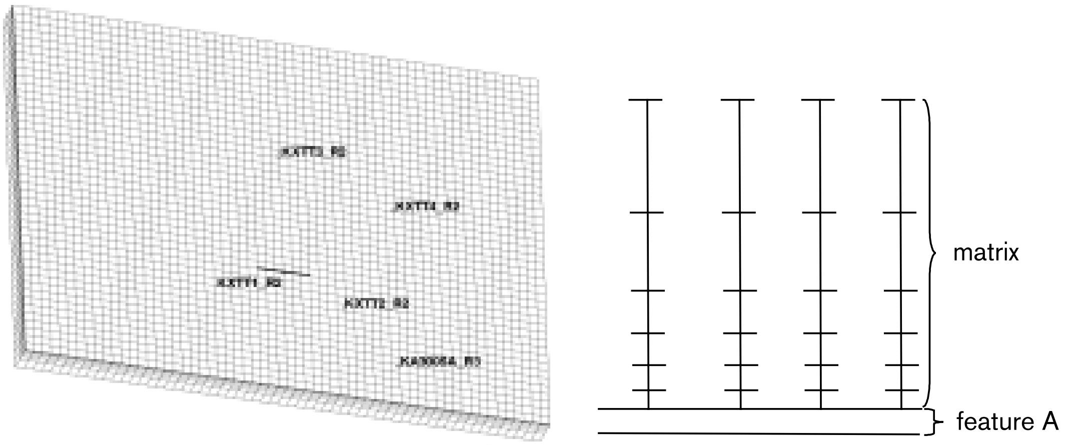
CRIEPI has taken part in the following two international co-operation tasks:

- Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task 6.
- Task Force on Engineering Barrier.

5.6.1 Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task 6

CRIEPI performed a numerical analysis for sub-task 6B2. A numerical code developed by CRIEPI for groundwater flow and solute transport in rock formations, FEGM, was used.

The analysis was performed by using mainly a 3D model where Feature A was represented as a single flat square of uniform aperture and the surrounding rock matrix was represented as a porous media block of 10 cm thickness on each side of Feature A, see Figure 5-43a. A 1D model based on a dual porosity model was also used for comparison, see Figure 5-43b. In the analysis of radionuclide migration with the three-dimensional model, the processes of advection and dispersion in Feature A and rock matrix, matrix diffusion and sorption to fracture surface, fault gouge, and rock matrix were taken into consideration. The transmissivity distribution in Feature A, the fracture aperture, and sorption coefficients on fault gouge were calibrated in simulations of the tracer test STT-1b (TRUE-1) and other tracer tests. Other input values were estimated mainly on basis of the results of laboratory experiments performed by SKB. Basically the same input values were used for both the 3D and the 1D models.



(a) Three-dimensional model (b) One-dimensional model

Figure 5-43. *Numerical model used for the analysis of Task 6B2.*

Figure 5-44 shows the calculated breakthrough curves of the tracers at the intersecting fracture which is 10 m downstream from the injection point, for pulse injection under the natural hydraulic gradient. Under the natural hydraulic gradient, the effects of matrix diffusion and sorption were relatively more prominent than under the pumping condition like in the STT-1b tracer test. The breakthrough curves calculated by using the 1D model reached its peak earlier and its peak values were larger than the ones calculated by using the 3D-model. Furthermore the former decreased more rapidly than the latter. It was concluded that due caution had to be exercised to predict the radionuclide migration in the rock by using a 1D model and the selection of the proper values of input parameters such as dispersion length becomes very important in such case.

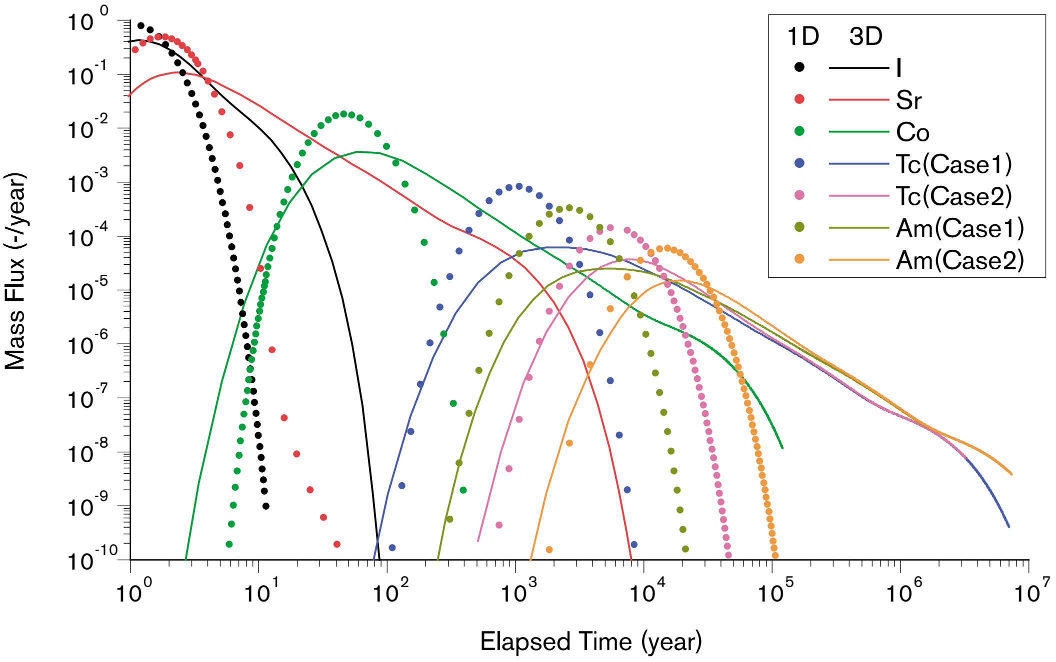


Figure 5-44. *Calculated breakthrough curves at downstream intersecting fracture for pulse injection.*

5.6.2 Task Force on Engineering Barrier

CRIEPI has been developing a coupling code that evaluates the phenomena that occurs in the engineering barrier system. This code is applied to an *in situ* experiment performed by JNC in Kamaishi mine. The experimental layout is based on the Japanese concepts of waste disposal. The geometry of the finite element mesh and the position of the temperature and water content monitoring point are shown in Figure 5-45. The red zone, orange zone, and green zone are heater, buffer material, and rock mass, respectively. The temperature on the heater was kept at 90°C for 200 days. The modelling accounts for density dependent thermal and moisture transport. The changes of temperature and water content are shown in Figure 5-46. The simulated results approximately agree with the measured data expect for the water content. The difference in water content is due to the fact that the vapour transport could not be modelled well enough. In the future, the code will be developed to simulate the water transport more accurately.

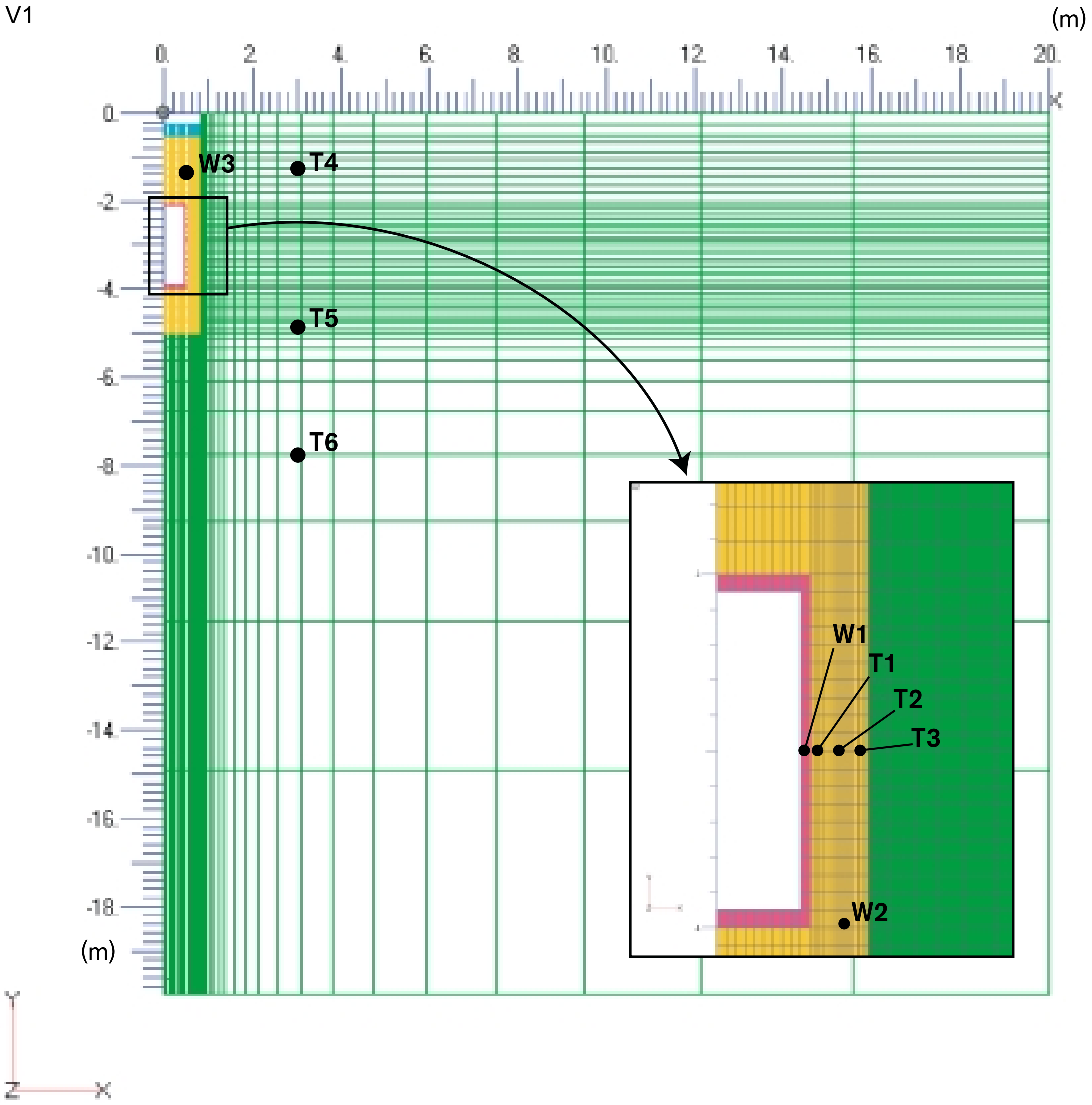


Figure 5-45. *Finite element mesh and monitoring point for temperature (T) and water ration (W).*

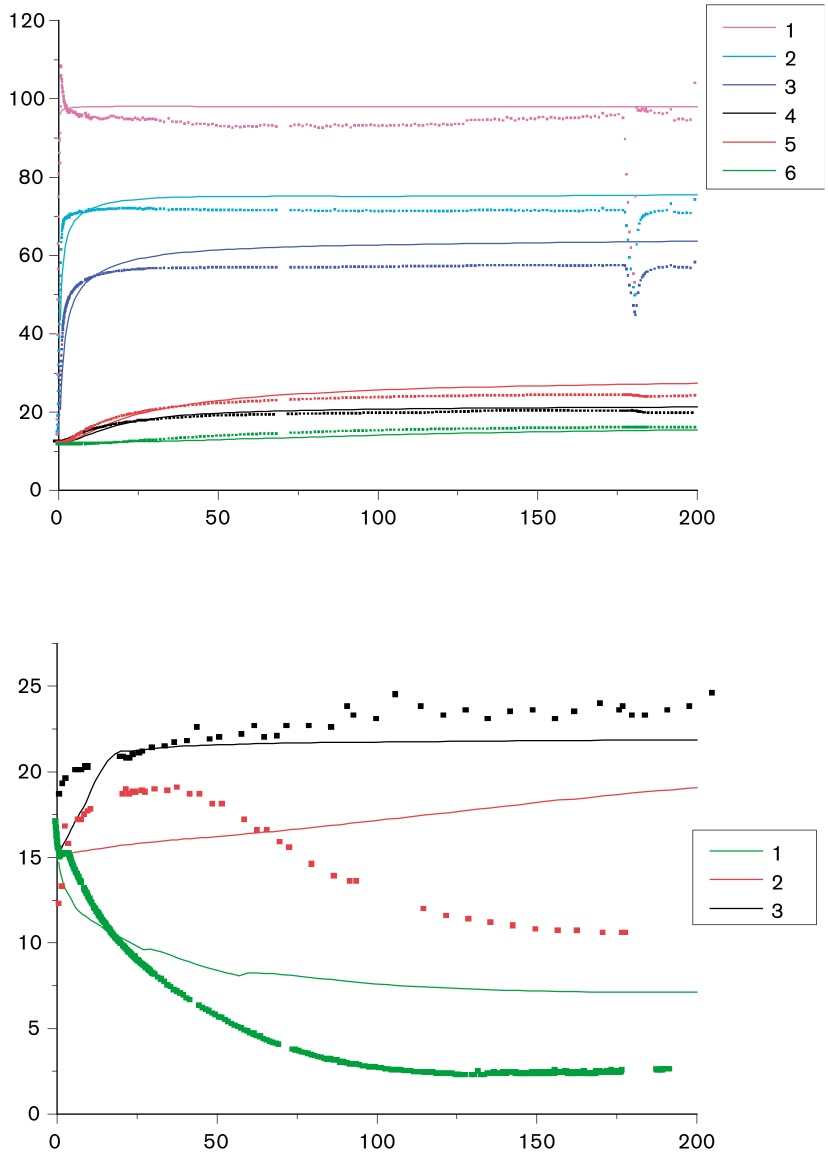


Figure 5-46. *Relationship between measured (symbols) and simulated results (lines).*

5.7 NAGRA

In 2002, Nagra (National Cooperative for the Disposal of Radioactive Waste, Switzerland) participated in Äspö projects primarily focussing on the natural barriers. The work carried under the support of Nagra has been fully integrated in the projects and is described in detail in the respective project sections. An outline is provided herein.

5.7.1 Matrix Fluid Chemistry

The project aimed to characterise the pore water composition within zones of very low permeability. This was conducted with laboratory experiments on drill core material and long-term *in situ* sampling of pore water that seeped into packed-off intervals over time periods of about 12 to 15 months. Laboratory experiments included the characterisation of the rock mineralogy, geochemistry, pore space accessible to water by various methods, diffusion experiments, crush/leach experiments, and geochemical modelling. *In situ* sampling included chemical and isotope analyses of the small water volumes obtained (10–120 ml per section) and hydraulic monitoring (performed by Geosigma).

Preparation of a report summarising the results was initiated (Matrix Fluid Experiment, J A T Smellie, H N Waber, S K Frape (eds)) and will be completed in the first half of 2003.

5.7.2 Task Force on Modelling of Groundwater Flow and Transport of Solutes

Nagra participated in the Task Force modelling meetings and workshops organised within the framework of the Task Force. In particular, Nagra (including University of Berne) participated in sub-task 6C of the Äspö Task Force, where the results of the Fracture Characterisation and Classification project were presented and discussed. The respective final report was delivered to SKB ("A semi-synthetic model of block scale conductive structures at the Äspö Hard Rock Laboratory", by /Dershowitz et al, 2003/).

5.7.3 Support to planning activities

Although not a participant to the corresponding projects, Nagra has had various discussions, also with the support of SKB, for the transfer of experience from Nagra projects to upcoming activities in Äspö. The following projects are particularly involved:

- Colloid Project.
- Tracer Retention Understanding Experiment – resin technology.
- Planning of the project concerning the KBS-3 method with horizontal displacement (e.g. contribute with experience from national and international collaborative projects).

5.8 Posiva

Posiva's participation to the work at Äspö HRL belongs mainly to the research and development of disposal technology and site evaluation. The following text comprises the work done during 2002 according to the joint projects. Posiva participated also to the feasibility study for development of the KBS-3 method with horizontal emplacement and to the EC-projects Prototype Repository and CROP.

5.8.1 TRUE Block Scale

The TRUE Block Scale project is an international project funded by ANDRA, ENRESA, Nirex, Posiva, JNC and SKB. It is part of Tracer Retention Understanding Experiments (TRUE). First part of the TRUE project has been conducted in a detailed scale (~ 5 m) and in a single feature. TRUE Block Scale experiments have been performed in a network of fractures with varying transport lengths of about 16–95 m.

The experiment is designed to study transport of tracers through a network fractures. During years 2000 and 2001 several different tracer tests have been carried out. Phase A tracer tests were focused on identifying the best pumping section, Phase B was carried out tests potential flow paths using non-sorbing tracers, and Phase C which included four different flow paths and large variety of different sorbing and non-sorbing tracers.

Results

During year 2002 evaluation of the Phase C tracer tests was finalised and the Posiva-VTT modelling report was also completed. Posiva-VTT team has also participated in the writing of the final reports of the TRUE Block Scale project.

5.8.2 Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task 6

Task 6 started at the end of the year 2000 and seeks to provide a bridge between site characterisation (SC) and performance assessment (PA) approaches to solute transport in fractured rock. It will focus on the 50 to 100 m scales, which is critical to PA according to many repository programmes.

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

Task 6 does not contain experimental work but it uses experimental results of the former Task 4. Task 4 was a series of tracer tests performed in single feature over transport distance of about 5 m using simple flow geometry and both conservative and sorbing tracers.

Results

Modelling of sub-task 6B2 was performed during year 2002. Sub-task 6B2 is an extension of the sub-task 6B to study transport over larger area of the Feature A. Moving from one flow path (sub-task 6B) to transport over a wider area of the fracture (sub-task 6B2) caused wider spread in the breakthrough than in the Task 6B. Modelling of the sub-tasks 6A, 6B and 6B2 was also reported during year 2002.

5.8.3 Long Term Test of Buffer Material

Posiva's task in the Long Term Test of Buffer Material (LOT) project is to study pore water chemistry in bentonite. The task will be carried out at VTT Processes.

The aim of the work carried out by VTT Processes 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

Analyses on the pore waters of the excavated one-year parcel (A0) were performed during the year 2002. Reporting of the results is underway.

5.8.4 Low-pH cementitious products

A feasibility study on the qualification of low-pH cementitious products in the deep repository has been carried out in 2002. The work has been divided into 7 different work packages, see Section 3.8.3, of which Posiva has been participating especially in the WP 5 (Grouting).

Results

The work performed in WP 5 is included in the description of the bedrock of Olkiluoto. Based on the result simple bedrock classes were created. The purpose of the classification was to describe different bedrock types (at three depth levels) from grouting point of view. Based on the bedrock properties KTH modeled the penetration of grouts to find necessary properties of suitable grouts for Olkiluoto site to be developed in the low alkaline cement project.

In WP 4 the practical installation techniques of rock bolts and required properties of the bolting grout has been described by Saanio & Riekkola Oy (S&R).

In WP 5 (Grouting) S&R has written a report of geological conditions at Olkiluoto site. Typical fracture systems that are important from grouting point of view were identified in co-operation with KTH. The report is compiled with KTH's report of grout properties.

Project management and planning of next stage is performed in WP 7. S&R has participated in planning and cost estimations of the large field test.

5.8.5 Pillar Stability Experiment

SKB is planning to perform a large-scale pillar stability experiment at Äspö HRL called APSE (Äspö Pillar Stability Experiment). The study is focused on understanding and controlling the progressive rock failure in a pillar and damages caused by high stresses.

The experiment was prior to the test execution modelled by different research groups using different analysis approaches. Posiva's contribution in 2002 was to perform preliminary three dimensional thermo-mechanical analyses. The work was carried out by Saanio & Riekkola Oy using the three dimensional element code FLAC^{3D} /Wanne and Johansson, 2003/.

Results

The modelling work consisted of two different test model geometries and different input data regarding the *in situ* stress state and rock properties. The results showed that the high enough stresses will be obtained to cause damages in the pillar. The heating of the rock induces a clear stress increase in the pillar area and after 120 days of heating the stress increase is approximately 40% higher than the pre-heating stress state at the deposition hole wall (see Figure 5-47 and Figure 5-48). The crack initiation strength of the host rock is exceeded at the top of the pillar area in each of the modelling cases. The crack damage strength and the peak strength are exceeded after 120 days of heating in every *in situ* stress state case with slots at the deposition hole wall.

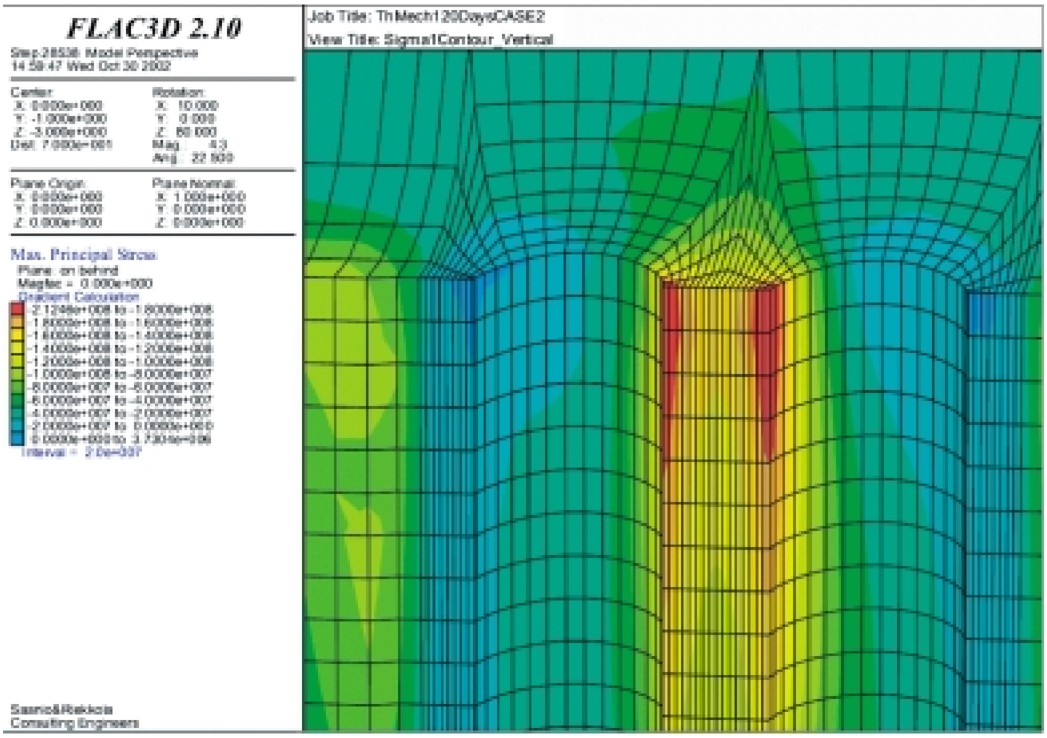


Figure 5-47. *Maximum principal stresses at the pillar area after 120 days of heating. FLAC^{3D} model with slots, maximum* in situ *stress 30 MPa. The maximum induced stress at the top of the pillar is about 210 MPa and at the first 3.5 m of the pillar the stresses are over 160 MPa.*

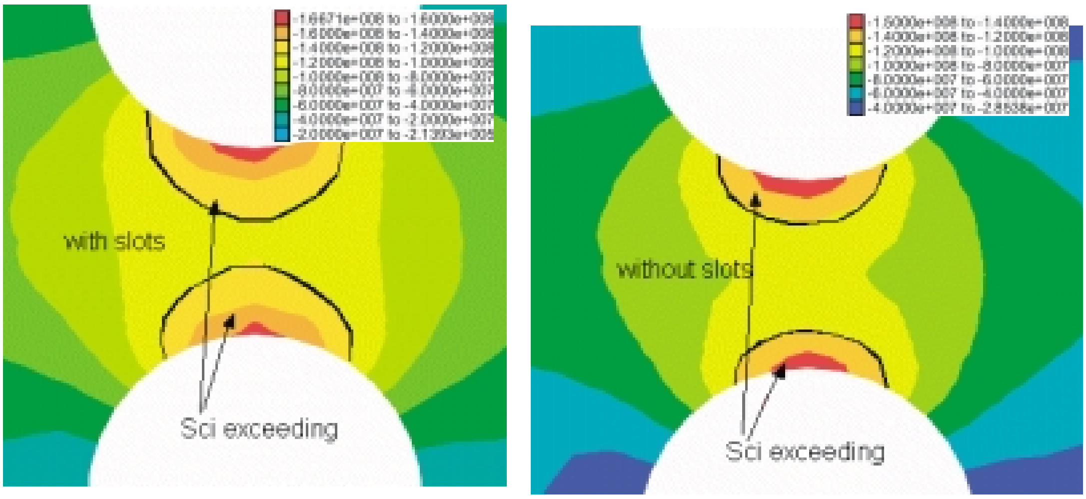


Figure 5-48. *Comparison of the maximum principal stress contours at the horizontal section at a level of 1.5 m below the tunnel floor after 120 days heating. Left the model with slots and right the model without slots. FLAC^{3D} model with the maximum* in situ *stress 25 MPa.*

5.8.6 Quality control of overcoring data

In situ stress measurements by overcoring (OC) of a so called 3D stress cell are used in both the Posiva and SKB rock mechanical programmes. The cell can theoretically provide the three principal stresses and their orientations. It is however known that due to various circumstances a test result may be erratic if the rock conditions differ from the basic assumption of linear elastic material or if no quality control is applied for different phases of field work.

As a part of SKB's project for establishing a total strategy for technical and quality control of OC results Posiva/Gridpoint Oy has developed a quality control tool and interpretation method for quality checks of the rock stress data emerged from OC measurements. The project is limited to continues, homogeneous, isotropic, and linearly elastic (CHILE) conditions.

The primary product of this sub-project is a computer program which computes strain change during OC and compares these to measured ones. The *in situ* state of stress can be calculated from measured transient strains also. The program is designed so that it can be extended to different OC methods but in this work the stress tensors are calculated only for Borre probe geometry. The computer program is developed in Microsoft Excel environment and the pre-calculation of stress tensors is done with FLAC^{3D}.

As a continuation for the work it was decided to study whether it is reasonable to extend the developed tool to transversally isotropic material, since there were indications that the rock types at Olkiluoto and Forsmark can have anisotropic behaviour, which has effect on overcoring stress measurements. The work was started by laboratory tests of Olkiluoto mica gneiss with 5 different anisotropy plane dip angles. If the deformation anisotropy is over 1.3 it is reasonable to continue the development. 10 uniaxial loading tests (two per foliation angle) out of the total number of 25 were conducted in 2002. Due to renovation work at the laboratory the loading machine (MTS) is out of use till the end of the year 2002 the tests can be completed at earliest in February, 2003. The preliminary results clearly indicate anisotropic behaviour: The factor of anisotropy on Young's modulus is order of 1.7.

5.9 USDOE CBFO/SNL

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

1. Validation of the multi-rate model using results from the TRUE-1 tracer tests conducted at the Äspö underground research laboratory.
2. Experimental visualisation of mass-transfer processes in low porosity rock.
3. Numerical experiments to understand the scaling of parameters defining mass-transfer from the tracer test scale up to the performance assessment scale.

Work on all three of these tasks was conducted in calendar year 2002. A summary of the work conducted on each topic is provided below.

SNL joined the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes in September of 1998 in order to be involved with the TRUE-1 tracer test planning and evaluation and better accomplish Task 1. A Task Force Meeting was held in 2002 in Äspö, Sweden in June and was attended by Sean A McKenna from SNL.

5.9.1 Task Force on Modelling of Groundwater Flow and Transport of Solutes

Topic 1

The objective of Topic 1 is to validate the multirate mass-transport model developed at Waste Isolation Pilot Plant (WIPP), the US DOE's deep geologic repository for transuranic nuclear waste, in a vastly different geologic environment. Previous work on Topic 1 was comprised of the prediction and estimation of the STT-1, STT-1b and STT-2 tracer tests and was completed as part of Äspö Task Force Task 4. In 2002, SNL work on Task 4 was finalised by compiling all modelling results and comparisons with laboratory data for development of a final report and journal article. This report and article will be written in 2003.

Task 6 of the Äspö Task Force is focused on the scaling of information from the tracer test scale to larger time and length scales. Work completed by SNL in 2002 includes the prediction of transport of Co, I, Tc, and Sr breakthrough curves under both pumping and ambient flow conditions within Feature A. These predictions were made using 100 stochastic transmissivity fields conditioned to the transmissivity measurements in Feature A and transport parameters derived from model fits to the STT-1b data. Work in 2002 focused on examining three different ways of up-scaling the transport parameters. These three techniques used to scale from the tracer test to the PA scale are: (1) using the same parameters at both scales; (2) maintaining a constant ratio of the diffusion rate to the velocity at both scales; and (3) maintaining a constant Damköhler number at both scales (example results are shown in Figure 5-49). Preliminary results of this scaling work were presented at the Task Force meeting in June.

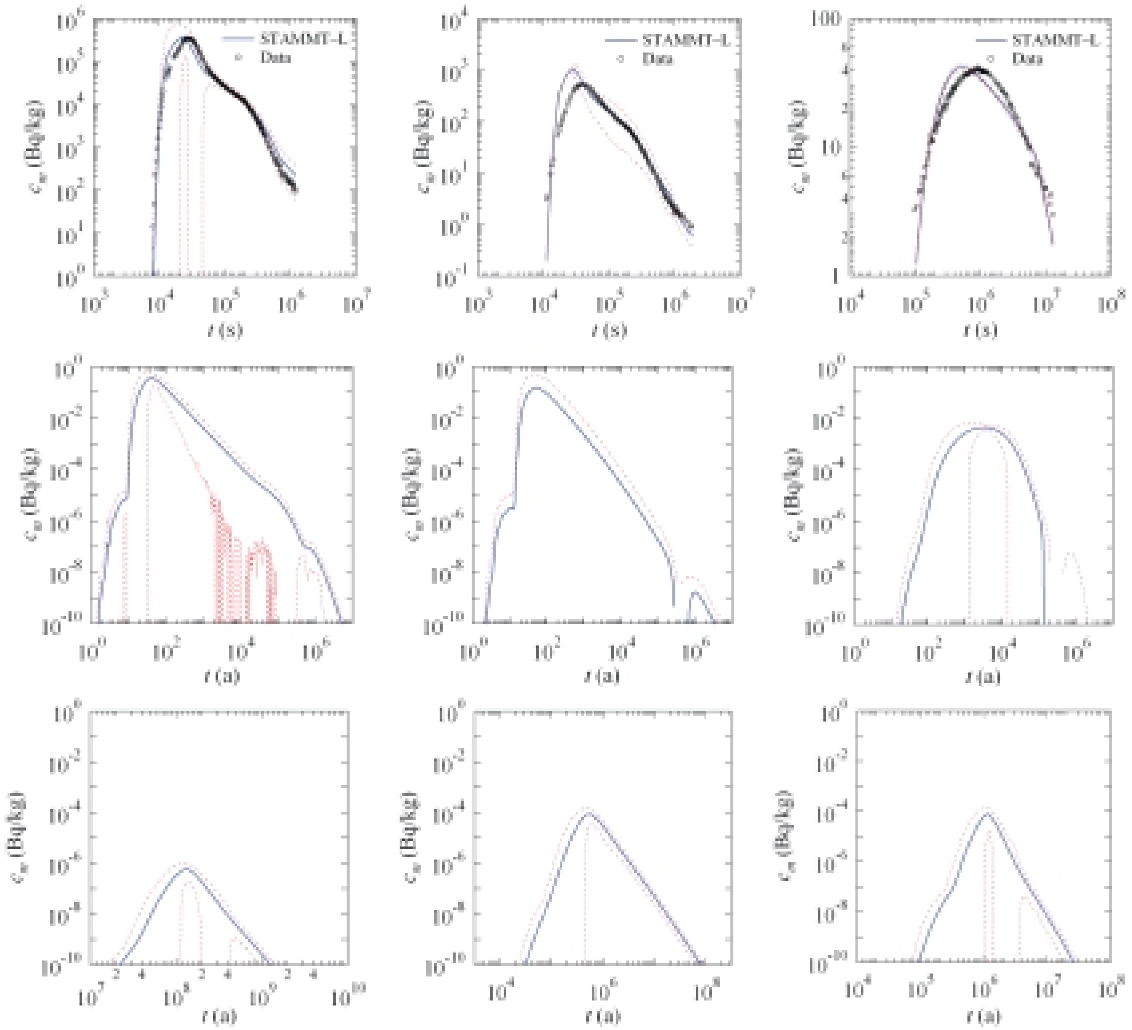


Figure 5-49. *Three sets of breakthrough curves for iodine, strontium, and cobalt (left, middle, and right images respectively). The top images are the model fits to the observed ST-1b data. The middle images are the breakthrough curves obtained by upscaling the diffusion rates to keep the ratio of diffusion rate to velocity constant. The lower images are the breakthrough curves resulting from keeping a constant Damköhler number from the tracer test to the PA scale. For each image, the blue line is the mean breakthrough curve and the red lines indicate +/– one standard deviation. The mean and standard deviations are calculated across 100 realisations of the transmissivity field.*

An offshoot of the work on the Äspö Task Force, Task 6 was the demonstration of the "Predictive Estimation" technique for addressing non-uniqueness in transmissivity fields created through stochastic inverse techniques and conditioned to both transmissivity and head measurements. Predictive Estimation was demonstrated on a hypothetical test case with advective transport calculations similar to those done in Feature A. We had hoped to use this technique to generate T-fields for Feature A, but the available head data did not allow for conditioning. A journal article on this approach to T-field estimation has been accepted for publication in a special issue of the *Journal of Hydrology* on stochastic inverse modelling as: McKenna S A, J Doherty and D B Hart. Non-Uniqueness of Inverse Transmissivity Field Calibration and Predictive Transport Modelling.

Topic 2

The objective of Topic 2 is to develop new techniques for the visualisation of mass-transfer processes in low porosity rock. Use of synchrotron based computed microtomography (CMT) allows for high-resolution, three-dimensional, non-destructive imaging necessary to characterise small-scale heterogeneities in lower-porosity rock cores. Images were taken of 5.5 mm diameter capillary tubes with different diameter pore space. These images were used to determine the minimum visible pore space and the threshold intensity value to use to distinguish pore space from solid. In addition, three rock samples from Japan, Switzerland and Sweden were exampled. The cores were approximately 5 mm in diameter. Samples were pressure saturated with 400 g/l iodine as KI.

The X-ray absorption properties of iodine are used to enhance the visualisation of pores in the samples. Samples were imaged at two different energies, above and below the absorption edge of iodine (33.2 keV). The absorption edge is the energy required to knock an electron from an outer shell of the atom. At the energy just below the absorption edge, the element is much less absorbing to X-rays than at energies immediately above the absorption edge. We subtracted the data arrays of the images obtained above the absorption edge from those taken below the absorption edge. If regions in the sample contain no iodine then the voxel values above and below the edge should be close to the same value, and results in zero intensity in the difference image. In contrast, if a sample region contains iodine then the voxel values in the difference image should be greater than zero and will appear as bright areas in the image. The difference image therefore enhances the visibility of the caesium in the sample. The voxel size for each sample was 9.57 μm on a side.

The pore space in the capillary tube with 51 μm pore space was clearly delineated in contrast to the 25 μm pore space (Figure 5-50). It can be inferred that the resolution of this imaging process is somewhere between 3 and 5 voxels, in this case between 25 and 50 μm.

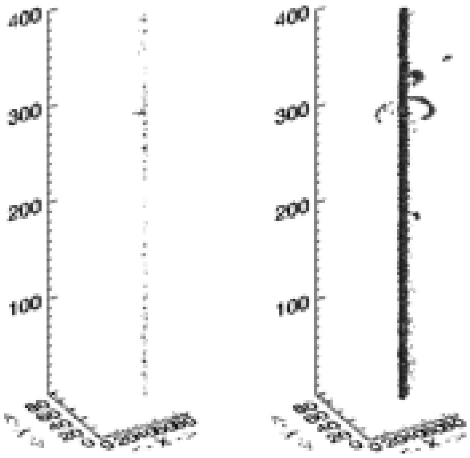


Figure 5-50. *Images of 25 μm diameter (A) and 51 μm diameter (B) pore space in capillary tubes. Voxels are 9.57 μm on a side.*

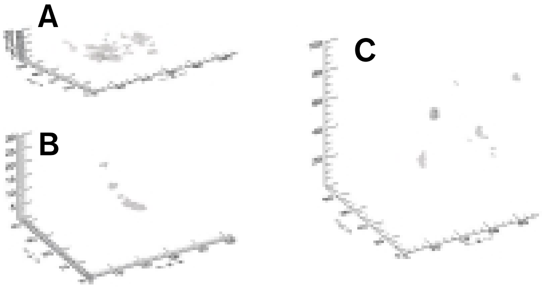


Figure 5-51. *Selective images of pore space in (a) granodiorite from Japan, (b) diorite from Sweden and (c) sheer-zone materials from Switzerland. Scales are number of voxel values where a voxel is 9.57 μm on a side.*

Pore-space was clearly delineated in the rock samples (Figure 5-51). The visualised pore space was in the interior of the core. There must be accessible pores space smaller than the resolution of CMT in order for the KI tracer to have accessed these volumes in the central portion of the cores. The porosity for each rock core was also calculated. These calculated porosity values were much smaller than expected based on previous measurements of the rock samples. This result also indicates that there is pore space important to flow and transport smaller than the resolution of this technique.

In summary, the resolution for imaging pore space was determined between 25–50 μm. It is thought that it could be as high as 15 μm if smaller samples were imaged. Pore space in the crystalline rock samples was visualised. However, it has been inferred that smaller-scale pore space important to flow and transport must be present.

Topic 3

Work on Topic 3 in 2002 was focused on finalising a draft journal article on the results of the transport scaling comparisons between the multi-rate model (STAMMT-L) and the single-rate model used in the SKB SR 97 report (FARF31). Significant findings from this work include the results that the FARF31 calculations 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. The draft journal has been submitted to *Hydrogeology Journal* as: Constraining Performance Assessment Models with Tracer Test Results: A Comparison of Two Conceptual Models by S A McKenna and J-O Selroos. Results in this article were also presented at the Äspö Task Force meeting in June.

5.10 EC-projects

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

5.10.1 Prototype Repository

SKB's reference concept for deep disposal of spent nuclear fuel, the KBS-3 concept, has several features in common with other European concepts and full-scale testing is therefore of great value. Components of this system have been thoroughly investigated but the Prototype Repository is the first full-scale application. The Prototype Repository is conducted at Äspö HRL as an integrated test focusing on Engineered Barrier System (EBS) performance but comprising also canister deposition, backfilling and plug construction. It offers a number of possibilities to compare test results with models and assumptions and also to develop engineering standards and quality assurance methods. The co-operative work aims at accomplishing confidence building as to the capability of constructing safe repositories and predicting EBS performance also for somewhat different conditions than those in the Äspö HRL.

In Sections 5.2–5.9 the information received from the participating organisations on achievements during 2002 can be found and an overview of the project status is given in Section 3.3.

Prototype Repository – Full scale testing of the KBS-3 concept for high-level radioactive waste

Start Date: 2000-09-01	**End Date**: 2004-02-29
Co-ordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries**: Finland, Germany, Japan, Spain, Sweden and United Kingdom

5.10.2 CROP

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

CROP – Cluster repository project, a basis for evaluating and developing concepts of final repositories for high level radioactive waste

Start Date: 2001-02-01	**End Date**: 2004-01-31
Co-ordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries**: Belgium, Canada, Finland, France, Germany, Spain, Sweden, Switzerland and USA

5.10.3 FEBEX II

The FEBEX project has the dual objective of demonstrating the feasibility of actually manufacturing and assembling an engineered barrier system and of developing methodologies and models for assessment of the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) behaviour within the engineered barrier system (near-field). FEBEX II consists in the extension of the operational phase of the FEBEX I *in situ* test. The *in situ* test is performed in a TBM-drift at the Test Site at Grimsel in Switzerland, where two full-scale canisters with electrical heaters have been installed horizontally. The canisters are surrounded by bentonite, pre-compacted into blocks possible to handle by man. The FEBEX II includes dismantling of the plug, retrieval of the outer canister and casting of a new plug. The FEBEX project also includes a mock-up test in scale 1:2, and some complementary laboratory tests, as well as modelling works.

The project has been extended 10 months due to the decision to investigate the saturation process longer than originally planned before dismantling the outer section.

FEBEX II – Full-scale engineered barriers experiment in crystalline host rock, Phase II

Start Date: 1999-07-01	**End Date**: 2004-10-31
Co-ordinator: Empresa Nacional de Residuos Radiactivos, Spain	**Participating countries**: Belgium, Czech Republic, Finland, France, Germany, Spain, Sweden and Switzerland

5.10.4 BENCHPAR

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

BENCHPAR – Benchmark tests and guidance on coupled processes for performance assessment of nuclear repositories

Start Date: 2000-10-01	**End Date**: 2003-09-30
Co-ordinator: Royal Institute of Technology (Dep. of Civil and Environmental Engineering), Sweden	**Participating countries**: Finland, France, Spain, Sweden and United Kingdom

5.10.5 ECOCLAY II

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

ECOCLAY II – Effects of cement on clay barrier performance, phase II

Start Date: 2000-10-01	**End Date**: 2003-09-30
Co-ordinator: National Radioactive Waste Management Agency of France	**Participating countries**: Belgium, Finland, France, Germany, Spain, Sweden, Switzerland and United Kingdom

5.10.6 SAFETI

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

SAFETI – Seismic validation of 3D thermo-mechanical models for the prediction of the rock damage around radioactive spent fuel waste

Start Date: 2001-09-01	**End Date**: 2004-09-01
Co-ordinator: The University of Liverpool (Dep. of Earth Sciences), United Kingdom	**Participating countries**: France, Sweden and United Kingdom

5.10.7 PADAMOT

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

PADAMOT – Palaeohydrogeological data analysis and model testing

Start Date: 2001-11-01	**End Date**: 2004-11-01
Co-ordinator: Nirex Ltd, United Kingdom	**Participating countries**: Czech Republic, Spain, Sweden and United Kingdom

5.10.8 NET.EXCEL

The objectives are a future efficient use of European resources in research and development of safe methods for final disposal of high-level radioactive waste calls for close interaction between European end users in planning of national programmes as well as in development of international projects. The proposal concerns the forming of a network of end users for the intended analysis of present status and future requirements in RTD for the three different rock media: salt, clay sediments and crystalline rock. The expected results are common and systematic basis for priorities and co-ordination of future European RTD work for radioactive waste management, and suggested areas and priorities for joint RTD projects. The objectives are to develop a common and systematic basis for priorities and co-ordination of future European RTD work for Radioactive Waste Management and suggest areas and priorities for joint RTD projects. This will be accomplished by forming a Network of Excellence with the main European organisations given the national responsibilities to develop systems for safe handling and disposal of long-lived radioactive waster and by jointly working out a document that can serve as an aid for the planning and execution of future co-ordinated RTD activities between European implementers.

NET.EXCEL – Network of excellence in nuclear waste management and disposal

Start Date: 2002-11-01	**End Date**: 2004-01-31
Co-ordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries**: Belgium, Finland, France, Germany, Spain, Sweden, Switzerland and United Kingdom

6 Environmental research

6.1 General

Äspö Environmental Research Foundation was founded 1996 on initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its recourses available for national and international environmental research. SKB's economic engagement in the foundation will be concluded during 2003.

On the initiative of the Äspö Environmental Research Foundation the University of Kalmar has set up the Äspö Research School. The research school is a concrete commitment to provide conditions for today's and tomorrow's research concerning environmental issues. The research school has a special interest in the transport of pollutants and their distribution in rock, ground, water, and biosphere. The research school is co-financed by the municipality of Oskarshamn, SKB, and the University of Kalmar. During 2003 detailed plans for the activities will be worked out and the goal is to let four doctorial students begin their studies. The number of students will be increased to about ten during the coming years.

In an agreement with the Äspö Environmental Research Foundation and the Geological Survey of Sweden (SGU) field experiments have been performed at Äspö HRL to investigate the retention and degradation of petroleum products at *in situ* conditions, see Section 6.2. SGU is a national authority responsible for questions relating to Sweden's geological character and handling of minerals. SGU also has responsibility for decommission of the national civilian stockpile of petroleum products.

6.2 Retention and biodegradation of petroleum hydrocarbons

6.2.1 Background

The processes that govern natural retardation and degradation of petroleum hydrocarbons in soil aquifers are relatively well understood, and this knowledge is supported by field studies at many sites. Knowledge about these processes is crucial for risk assessments and decisions about remedial actions at sites where the groundwater is contaminated. However, the environmental impact of a petroleum spill into a crystalline rock environment is much more difficult to predict. The heterogeneity and inaccessibility of such formations complicates site-specific investigations of groundwater flow and contaminant fate and transport. Furthermore, very little data is available to support more general assessments of contaminant retardation and degradation at these sites.

Since 1996, research on microbiological degradation of petroleum components in crystalline rock surrounding petroleum storage facilities has been carried out at the University of Gothenburg and Chalmers University of Technology. The research programme, which is financed by the Geological Survey of Sweden, SGU, was initiated to provide a scientific basis for environmental risk assessment and remediation actions in connection with the decommissioning of a large number of petroleum storage facilities in Sweden. Until recently, the programme has been focused on laboratory investigations of degradation processes. The present experiment at Äspö HRL is a continuation and "up-scaling" of these laboratory studies.

Literature reviews show no results from field experiments at larger scales published in the scientific literature.

The Redox zone at Äspö HRL has been identified as a suitable site for conducting field scale experiments within SGU's research programme. The fieldwork started in 2001 and will be finished in April 2003.

6.2.2 Objective

The main objective with the experiment is to develop a better understanding of the effects of retention and biodegradation of dissolved aromatic hydrocarbons in water filled fractures in crystalline rock.

SGU intends to use this knowledge to improve risk assessments and to provide more relevant monitoring programmes for decommissioned petroleum storage facilities in rock caverns.

6.2.3 Experimental concept

Methodology: Conservative tracers and degradable test substances are injected into the fracture zone and the responses are measured. Propylbenzene is used as test substance, as a substitute for the more toxic substance benzene. Fluorescent dyes (e.g. uranine) are used as conservative tracers. Both injection and breakthrough curves of tracer and test substance are measured. To study microbiological processes, degradation products, water chemistry and microbiological analyses are also performed.

Configurations: Two different configurations of injection and extraction boreholes have been used: 45 m below ground surface (b.g.s.) in HBH01 to the core drilled borehole KR0013B at 70 m b.g.s. in the tunnel, and 15 m b.g.s. in HBH01 to KR0013B in the tunnel.

Installations: The boreholes are equipped with packers of stainless steel. In boreholes HBH01 and HBH02, dummies of stainless steel are installed to decrease the borehole volume. All tubing in contact with the test substance is made of stainless steel. Sampling and injection equipments are placed in a container above HBH02 at Bockholmen. Other sampling and monitoring equipment are placed in the Redox niche in the tunnel.

The experiment consists of the following parts:

- Borehole status investigation and conditioning.
- Well- and field site installations.
- Updated hydraulic characterisation of the zone, including tracer tests with conservative tracers.
- Test of break through of propylbenzene, configuration "HBH01 –> KR0013B" (where HBH01 is injection borehole and KR0013B is extraction borehole).

- Test of microbiological activity, configuration “HBH01 –> KR0013B”.
- Main experiment: Retention and degradation of propylbenzene, configuration “HBH02 –> KR0013B via HBH01”.

6.2.1 Results

The injection of propylbenzene in configuration “HBH01 –> KR0013B” shows that it is possible to get breakthrough in detectable concentrations, see Figure 6-1.

Indications on microbiological activity have been obtained when injecting easily degradable lactic acid in configuration “HBH01 –> KR0013B”.

The main experiment in the configuration from HBH02 to the tunnel is going on. The results obtained so far show a break through for propylbenzene that is very different from the conservative tracer, indicating substantial mass loss of propylbenzene.

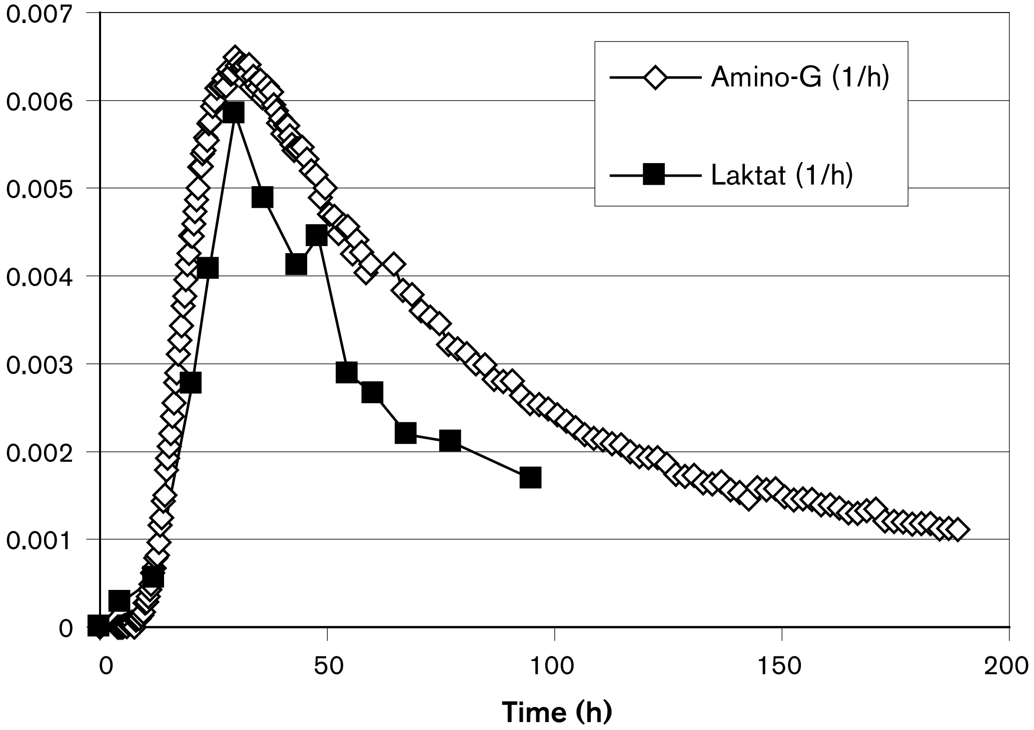


Figure 6-1. *Normalised concentrations in extraction borehole KR0013B after injection in HBH01.*

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